

ERRATA

- Page XIV Instead of (...) Exercise protocol with (A) cycle ergometer and (B) swimming snorkel AquaTrainer performed at three different intensities (...) read (...) Exercise protocol swimming pool (A) and on a cycle ergometer (B) performed with an AquaTrainer® prototype with 2 (SV2) and 4 valves (SV4), and with a standard mask (Mask) at 3 different intensities (...)
- Page L Instead of (...) Exercise protocol with (A) cycle ergometer and (B) swimming snorkel AquaTrainer performed at three different intensities (...) read (...) Exercise protocol swimming pool (A) and on a cycle ergometer (B) performed with an AquaTrainer® prototype with 2 (SV2) and 4 valves (SV4), and with a standard mask (Mask) at 3 different intensities (...)
- Page LIII Instead of the (...) expiratory tube is shorter (from 128 cm to 86 cm) and the inspiratory tube is longer (from 128 cm to 86 cm) (...) read (...) expiratory tube is shorter (from 196 cm to 86 cm) and the inspiratory tube is longer (from 55cm to 86cm) (...)



UNIVERSIDADE
DO PORTO
FACULDADE
DE DESPORTO

CENTRO
DE INVESTIGAÇÃO
FORMAÇÃO
INOVAÇÃO
E INTERVENÇÃO
EM DESPORTO
CIF2D



UNIVERSITY OF PORTO

Faculty of Sport

Centre of Research, Education,

Innovation and Intervention in Sport

Biophysical determinants of front crawl locomotion. A study conducted at different swimming intensities.

Academic dissertation submitted with the purpose of obtaining a doctoral degree in Sports Sciences according to the Decree-Law 74/2006 from March 24th.

Supervisors:

Prof. Dr. Ricardo J. Fernandes

Prof Dr. João Paulo Vilas-Boas

Prof. Dr. Huub Toussaint

João António Martins Ribeiro

Porto, December 2015

Ribeiro, J. (2015). Biophysical determinants of front crawl locomotion. A study conducted at different swimming intensities. Doctoral Thesis in Sport Sciences. Centre of Research, Education, Innovation and Intervention in Sport. Faculty of Sport, University of Porto.

KEY WORDS: SWIMMING, FRONT CRAWL, EFFICIENCY, POWER, DRAG, ENERGY

Funding

This Doctoral Thesis was supported by the Portuguese Science and Technology Foundation (FCT) grants SFRH/BD/81337/2011 and PTDC/DES/101224/2008 (FCOMP -01-0124-FEDER-009577).



Acknowledgments

To my supervisor Prof. Dr. Ricardo Fernandes for the guidance, patience, real commitment and for the constant stimulus to fulfil this goal.

To Prof. Dr. João Paulo Vilas Boas for sharing his knowledge and for all the entire support through my academic career.

To Prof. Dr. Huub Toussaint for all the support, academic debates and for refreshing my ideas.

To Prof. Dr. Pedro Figueiredo for his valuable intellectual participation and true friendship.

To Prof. Dr. Argyris Toubekis for all the comments, questions, new ideas and friendship.

To Prof. Dr. Carlo Baldari for all the assistance and friendship.

To Prof. Dr^a. Susana Soares that accompany me along this journey.

To Prof. Dr. Leandro Machado for helping me in math issues.

To Prof. Dr. Joaquim Monteiro for his valuable help and friendship.

To Prof. Dr. Kari Keskinen, Prof. Dr^a Laura Guidetti and Prof. Dr. Francisco Alves for their co-authorships and professionalism.

To Eng. Pedro Gonçalves for the patience, support and availability.

To Dr. Teresa Marinho for helping to improve my English competencies.

To all those that were directly and indirectly involved in the data collection, namely swimmers, coaches, professors, fellow researchers and faculty staff.

To Ana for her valuable support, particularly in the final stages of this process

To my working partners and friends for the support, friendship and academic debates.

To my family, without whom, would have been impossible to achieve this goal.

This Doctoral Thesis is based on the following scientific papers, which are referred in the text by their Arabic and Roman numerals, respectively:

1. Ribeiro, J., De Jesus, K., Figueiredo, P., Toussaint, H., Guidetti, L., Alves, F., Vilas-Boas, J.P., Fernandes, R.J. (2013). Biomechanical determinants of force production in front crawl swimming. **Journal of Sports Medicine and Physical Fitness**, 53 (1-3), 30-37.
2. Ribeiro, J., Figueiredo, P., Guidetti, L., Alves, F., Toussaint, H., Vilas-Boas, J.P., Baldari, C., Fernandes, R. J. (2015). AquaTrainer® snorkel does not increase hydrodynamic drag but influences turning time. **International Journal of Sports Medicine**, DOI: 10.1055/s-0035-1555859.
3. Ribeiro, J., De Jesus, K., Sousa, M., Figueiredo, P., Keskinen, K., Vilas-Boas, J.P., Fernandes, R. J. (2015). Metabolic and ventilatory thresholds assessment in front crawl swimming. **Journal of Sports Medicine and Physical Fitness**, 55 (7-8), 701-707.
4. Ribeiro, J., Toubekis, A., Figueiredo, P., De Jesus, K., Toussaint, H., Alves, F., Vilas-Boas, J.P., Fernandes, R. J. Biophysical determinants of front crawl swimming at moderate and severe swimming intensities. Submitted for publication to **International Journal of Sports Physiology and Performance**.
5. Ribeiro, J., Morais, S.T. Figueiredo, P., De Jesus, K., Vilas-Boas, J.P., Fernandes, R. J. (2014). Effect of fatigue in spatiotemporal parameters during 100 m front crawl event monitored through 3D dual-media automatic tracking. In: Mason, B. (Ed.), *Proceedings of the XII International Symposium for Biomechanics and Medicine in Swimming* (pp. 218-222). Australian Institute of Sport. Canberra, Australia

6. Ribeiro, J., Figueiredo, P., Sousa, A., Monteiro, J., Pelarigo, J., Vilas-Boas, J.P., Toussaint, H., Fernandes, R. J. (2015). VO₂ kinetics and metabolic contributions during full and upper body extreme swimming intensity. **European Journal of Applied Physiology** 115, 1117-1124.

7. Ribeiro, J., Figueiredo, P., Morais, S.T., Alves, F. Toussaint, H., Vilas-Boas, J.P., Fernandes, R. J. (2015). How distinct level swimmers organise their biomechanics, energetics and coordination during extreme swimming intensity? Submitted for publication to **Journal of Sports Sciences**.

I. Fernandes, R.J., Ribeiro, J., Figueiredo, P., Seifert, L., Vilas-Boas, J.P. (2012). Kinematics of the hip and body center of mass in front crawl. **Journal of Human Kinetics**, 33, 15-23.

II. Baldari, C., Fernandes, R.J., Meucci, M., Ribeiro, J., Vilas-Boas, J.P., Guidetti, L. (2013). Is the new AquaTrainer® snorkel valid for VO₂ assessment in swimming? **International Journal of Sports Medicine**, 34 (4), 336-344.

Table of Contents

Acknowledgments	V
List of Publications	VII
Index of Figures	XI
Index of Tables	XVII
Index of Equations	XXI
Abstract	XXIII
Resumo	XXV
Résumé	XXVII
List of Abbreviations	XXIX
 Chapter 1 - General Introduction.	 1
 Chapter 2 - Biomechanical determinants of force production in front crawl swimming.	 9
 Chapter 3 - AquaTrainer® snorkel does not increase hydrodynamic drag but influences turning time.	 23
 Chapter 4 - Metabolic and ventilatory thresholds assessment in front crawl swimming.	 37
 Chapter 5 - Biophysical determinants of front crawl swimming at moderate and severe intensities.	 51
 Chapter 6 - Effect of fatigue in spatiotemporal parameters during 100 m front crawl event monitored through 3D dual-media automatic tracking.	 69
 Chapter 7 - VO_2 kinetics and metabolic contributions during full and upper body extreme swimming intensity.	 77

Chapter 8 - How distinct level swimmers organise their biomechanics, energetics and coordination during extreme swimming intensity?	95
Chapter 9 - General Discussion	115
Chapter 10 - Conclusions	123
Chapter 11 - Suggestions for Future Research	125
Appendix I - Kinematics of the hip and body center of mass in front crawl.	XXXI
Appendix II - Is the New AquaTrainer® Snorkel valid for VO ₂ Assessment in Swimming?	XLV
References	LXV

Index of Figures

Chapter 2	<p>Figure 1. System to measure active drag (MAD-system, left panel) and respective force transducer (right panel).</p> <p>Figure 2. Comparison between free swimming (black) and MAD-system (gray) conditions for the normalized velocity (left panel) and the normalized stroke frequency (SF, right panel) at each velocity. * Significant difference between the two conditions, $P < 0.05$.</p> <p>Figure 3. Relationship between force and velocity (a), stroke frequency (b) stroke length (c), intracyclic velocity variations (d), index of coordination (e) and propelling efficiency (f) average for the ten swimmers.</p>	<p>13</p> <p>17</p> <p>19</p>
Chapter 3	<p>Figure 1. Typical individual example (left panel) and poll sample (right panel) active drag-velocity curves when swimming without and with the AquaTrainer® snorkel.</p> <p>Figure 2. Passing-Bablok analysis (left panel, the solid and dashed lines indicate the regression equations and the identity, respectively) and Bland-Altman plots (right panel, the solid and dashed lines indicate mean difference and 95% confidence interval, respectively) of the differences in active drag obtained swimming without and with the AquaTrainer® snorkel for</p>	<p>29</p> <p>31</p>

each studied velocity.

Chapter 4	Figure 1. Example of blood lactate concentration ($[La^-]$) and pulmonary ventilation (V_E) to velocity curves for metabolic and ventilatory anaerobic thresholds assessment. The interception of a linear and exponential lines are represented.	43
	Figure 2. Comparison between the metabolic and ventilatory thresholds by Bland and Altman scatter of plots for velocity (left panel) and heart rate (right panel). Average difference line (solid lines) and 95% CI (dashed lines) are indicated.	45
	Figure 3. Bland-Altman trend plot considering the linear relationship between the paired difference ($v@AnT_{Met} - v@AnT_{Vent}$) and the average velocity. Average difference trend line (dashed line) is also represented.	45
Chapter 5	Figure 1. Stroke frequency (SF), stroke length (SL), propelling efficiency (η_P), index of coordination (IdC), power to overcome drag (P_D), metabolic power (\dot{E}) and performance efficiency (η_D) values obtained at both anaerobic threshold (v_{AnT} , upper panel) and maximal oxygen uptake ($\dot{V}O_{2max}$; lower panel) intensities for each studied swimmer.	59
Chapter 6	Figure 1. Full-body marker setup: (a) swimmer, (b) acquired in Qualisys Track Manager, and (c) post processed using Visual3D.	72

Chapter 7	<p>Figure 1. Typical example of a swimmer's oxygen uptake ($\dot{V}O_2$) kinetics during an extreme intensity swimming bout (100 m front crawl) using full body and upper body only.</p>	85
	<p>Figure 2. Typical example of a swimmer's oxygen uptake ($\dot{V}O_2$) kinetics normalized to $\dot{V}O_{2peak}$ and time percentage during extreme intensity swimming bout (100 m front crawl) using full body and upper body only.</p>	86
	<p>Figure 3. Total energy expenditure derived from aerobic, anaerobic lactic and alactic energy sources in the maximal 100 m front crawl conditions.</p>	87
Chapter 8	<p>Figure 1. Mean (\pm SD) values of speed and power output (left and right panels, respectively) for high and low-speed swimmers in each 25 m lap of the free 100 m maximal effort.</p>	104
	<p>Figure 2. Mean (\pm SD) values of stroke frequency (SF) and stroke length (SL) values for high and low-speed swimmers in each 25 m lap of the free 100 m maximal effort (left panel). The normalised SF of the pool sample is also presented during unimpeded and MAD-system (black and grey bars, respectively) conditions (right panel).</p>	105
	<p>Figure 3. Mean (\pm SD) values of index of coordination values for high- and low-speed</p>	106

swimmers in each 25 m lap of the free 100 m maximal effort.

Figure 4. Mean (\pm SD) values of propelling efficiency and energy cost values (left and right panels, respectively) for high and low-speed swimmers (circles and squares, respectively) in each 25 m lap of the free 100 m maximal effort. 106

Appendix I **Figure 1.** Example of the intracyclic velocity variations of the hip (dashed line) and of the centre of mass (continuous line) for one swimmer. XXXIX

Appendix II **Figure 1.** Exercise protocol with (A) cycle ergometer and (B) swimming snorkel AquaTrainer® performed at three different intensities (Int 1: low intensity, Int 2: moderate intensity, Int 3: high intensity). CC, Change Condition; CR, Complete Recovery. L

Figure 2. Upper (A), frontal (B) and lateral (C) (dead space delimited in dotted line) representation of the AquaTrainer® prototype system. 1 = Mouthpiece, 2 = lower expiration valve, 3 = lower inspiration valve, 4 = neck connection, 5 = head connection, 6 = expiration tube, 7 = inspiration tube, 8 = upper expiration valve, 9 = upper inspiration valve, 10 = connection tubes unit. LII

Figure 3. Passing-Bablok regression and difference of oxygen consumption ($\dot{V}O_2$) obtained LVII

during swimming and cycling tests between the standard mask (Mask), the 2 (SV2) and 4 (SV4) valves. For each one of the four main graphs is reported the Passing-Bablok regression plot (the outside panel), with the linear regression (solid line), the identity (dashed line) and the equation with the Pearson's determinant coefficient (R^2), and the Bland-Altman plot (upper-left panel) with the mean difference (solid lines) and the 95% CI (dashed lines).

Figure 4. Passing-Bablok regression and difference of carbon dioxide production (VCO_2) obtained during swimming and cycling tests between the standard mask (Mask), the 2 (SV2) and 4 (SV4) valves. For each one of the four main graphs is reported the Passing-Bablok regression plot (the outside panel), with the linear regression (solid line), the identity (dashed line) and the equation with the Pearson's determinant coefficient (R^2), and the Bland-Altman plot (upper-left panel) with the mean difference (solid lines) and the 95% CI (dashed lines).

LVIII

Figure 5. Passing-Bablok regression and difference of Pulmonary ventilation (V_E) obtained during swimming and cycling tests between the standard mask (Mask), the 2 (SV2) and 4 (SV4) valves. For each one of the four main graphs is reported the Passing-Bablok regression plot (the outside panel), with the linear regression (solid line), the identity (dashed line) and the equation

LIX

with the Pearson's determinant coefficient (R^2), and the Bland-Altman plot (upper-left panel) with the mean difference (solid lines) and the 95% CI (dashed lines).

Index of Tables

Chapter 2	Table 1. Correlations coefficients among the studied variables. Significant correlation (r) at $P < 0.05$.	17
	Table 2. Regression modelling between force (F) and velocity (v), stroke frequency (SF), stroke length (SL), intracyclic velocity variations (IVV), index of coordination (IdC) and propelling efficiency (η_p).	18
Chapter 3	Table 1. Mean \pm SD active drag values during both swimming without and with the AquaTrainer® snorkel conditions. The p value and 95% confidence interval (95% CI) are also presented.	31
Chapter 4	Table 1. Anthropometric characteristics of male swimmers ($n=28$) and metabolic and ventilatory parameters assessed during the intermittent incremental swimming protocol.	44
Chapter 5	Table 1. Mean \pm SD values for stroke frequency (SF), stroke length (SL), propelling efficiency (η_p), power to overcome drag (P_D), index of coordination (IdC), oxygen uptake ($\dot{V}O_2$), lactate concentrations ($[La^-]$), metabolic power (\dot{E}) and performance efficiency (η_D) obtained at anaerobic threshold (AnT) and maximal oxygen uptake ($\dot{V}O_{2max}$) front crawl intensities, representing the moderate and severe swimming domains. Percentage and statistical significant differences (*; $p \leq 0.05$) between swimming intensities are also presented.	61

	Table 2. Pearson correlation values between velocities at anaerobic threshold (v_{AnT}) and maximal oxygen uptake ($\dot{V}O_{2max}$) and stroke frequency (SF), stroke length (SL), propelling efficiency (η_p), power to overcome drag (P_D), index of coordination (IdC), metabolic power (\dot{E}) and performance efficiency (η_D) at moderate and severe intensities, respectively. Significant level values are shown by * ($p \leq 0.05$).	62
Chapter 6	Table 1. Mean \pm SD and statistical comparisons between the laps across the 100 m race for general biomechanical parameters.	74
	Table 2. Mean \pm SD and statistical comparisons between the laps across the 100 m race for general biomechanical parameters.	74
Chapter 7	Table 1. Mean \pm SD of time duration, speed, peak oxygen uptake ($\dot{V}O_{2peak}$), oxygen uptake amplitude (A) and time constant (τ), as well as maximal lactate concentrations ($[La^-]_{max}$), after the maximal 100 m front crawl bouts performing with full body (S_{full}) and upper body only (S_{upper}).	85
Appendix I	Table 1. Mean \pm SD values of velocity and displacement of the centre of mass and hip, and the mean error, root mean square (RMS) error and percentage error. Mean intraclass correlation coefficient (ICC) between hip and centre of mass is also displayed (n=16).	XXXVIII

Table 2. Mean \pm SD values of the centre of mass and hip velocity related variables (p value is also shown).
The mean and RMS errors are also displayed (n=16). XXXIX

Appendix II **Table 1.** Agreement values obtained by the snorkel AquaTrainer® with 2 (SV2) and 4 (SV4) valves and the standard mask (Mask) in swimming and cycling assessed by Passing-Bablok regression analysis. LV
Pearson's determinant coefficient (R^2), mean difference, slope and intercept of the differences are reported.

Index of Equations

Chapter 1	Equation 1.	$v = SF \times SL$	1
	Equation 2.	$v = E/C$	2
	Equation 3.	$C = W_d/(\eta_p \times \eta_o)$	2
	Equation 4.	$\eta_o = P_o/E$	3
	Equation 5.	$\eta_D = P_D/E$	3
Chapter 2	Equation 1.	$D = A.v^n$	14
	Equation 2.	$CV = SD.mean^{-1}$	15
	Equation 3.	$n_p = \left(\frac{v}{2} \cdot \pi \cdot SF \cdot L\right) \cdot (2/\pi)$	15
	Equation 4.	$1 - [(30 - IdC)/60]$	16
Chapter 3	Equation 1.	$D = A.v^n$	28
Chapter 5	Equation 1.	$D = A.v^n$	58
Chapter 7	Equation 1.	$\dot{V}O_2 = \dot{V}O_{2b} + A \times (1 - e^{(-t/\tau)})$	82
	Equation 2.	$AnL = \beta \times [La]_{net} \times M$	83
	Equation 3.	$AnAl = PCr(1 - e^{(-t/\tau)}) \times M$	83
Chapter 8	Equation 1.	$AnL = \beta \times [La]_{net} \times M$	101
	Equation 2.	$AnAl = PCr\left(1 - e^{(-\frac{t}{\tau})}\right) \times M$	101

Abstract

Understanding the biophysical determinants of swimming locomotion is fundamental to enhance performance and achieve high-standard levels in competitive swimming. The purpose of this Thesis was to identify and characterise front crawl biophysical performance determinants at different swimming intensities. Experiments consisted of two front crawl intermittent incremental protocols of 7 x 200 m and 12 x 25 m (on the MAD-system), as well as a 100 m maximal front crawl swim. Kinematics, energetics and power were assessed through 3D reconstructions, oxygen uptake plus blood lactate concentrations and force measurements, respectively. Results pointed out that higher front crawl force production was reached through the increase in stroke frequency and, consequently, in velocity, which necessarily required a coordinative adaptation. Considering that the used respiratory snorkel did not lead to additional drag, at front crawl moderate intensity the anaerobic ventilatory and metabolic (evaluated using lactate concentrations) thresholds revealed to be proportional to each other. Performance at this swimming intensity was not explained by general stroking parameters, propelling and performance efficiency and metabolic and mechanical power, but was directly related to the velocity at maximal oxygen uptake (severe intensity domain). Contrarily to the moderate domain, front crawl performance at severe intensity was partially described by power to overcome drag and performance efficiency. At extreme front crawl intensity, spatiotemporal parameters were influenced by the induced fatigue and the energy contribution accounted with similar aerobic and anaerobic (lactic and alactic) participations. Moreover, with the exception of coordination, the stroke frequency, stroke length, propelling efficiency and energy cost profiles were not performance discriminative, but higher velocities were achieved due to superior power output, propelling efficiency and stroke frequency, leading to a higher index of coordination.

Key words: Swimming, Front crawl, Threshold, Efficiency, Power, Drag, Energy.

Resumo

Compreender os determinantes biofísicos da locomoção na natação é fundamental para melhorar a performance e atingir altos níveis competitivos. O objetivo desta tese foi identificar e caracterizar os determinantes biofísicos do rendimento da técnica de crol em diferentes intensidades de nado. Os testes consistiram de dois protocolos incrementais intermitentes de 7 x 200 m e 12 x 25 m (no MAD-system) bem como 100 m à velocidade máxima. A cinemática, a energética e a potência foram avaliadas através de reconstrução 3D, consumo de oxigénio e concentrações de lactato sanguíneo e a medição da força, respetivamente. Os resultados obtidos evidenciaram que valores elevados de produção de força foram atingidos através do aumento da frequência gestual e consequentemente da velocidade, o que requereu, necessariamente, uma adaptação coordenativa. Considerando que o uso da máscara respiratória (snorkel) não produziu qualquer arrasto adicional, na intensidade moderada os patamares ventilatório anaeróbico e metabólico (avaliados através das concentrações de lactatos) revelaram serem proporcionais entre si. A performance nesta intensidade de nado não foi explicada pelos parâmetros biomecânicos gerais, pela propulsão e eficiência da performance ou pela potência mecânica e metabólica, tendo sido diretamente relacionada com a velocidade ao consumo máximo de oxigénio (no âmbito da intensidade severa). Contrariamente à intensidade moderada, a performance de crol na intensidade severa foi parcialmente descrita pela potência para ultrapassar o arrasto e a eficiência do rendimento. Na intensidade extrema, os parâmetros espaciotemporais foram influenciados pela fadiga induzida e pela contribuição de energia contabilizada igualmente com participações aeróbicas e anaeróbicas (láticas e aláticas). Ainda, com a exceção da coordenação, os perfis da frequência gestual, distância de ciclo, a eficiência propulsiva e energia não foram fatores discriminativos do rendimento, mas velocidades mais elevadas foram atingidas devido à grande produção de potência, de eficiência propulsiva e frequência gestual, conduzindo a um índice de coordenação mais alto.

Palavras-chave: Natação, Crol, Limiar, Eficiência, Potência, Arrasto, Energia.

Résumé

Il faut comprendre les déterminantes biophysiques du déplacement en natation pour améliorer la performance et atteindre des standards élevés dans la natation de compétition. Le but de cette thèse était d'identifier et de caractériser les déterminantes biophysiques de la performance à différentes intensités de nage. L'investigation a consisté en deux protocoles incrémentaux intermittents en front crawl technique de 7 x 200 m et de 12 x 25 m (en MAD-système), ainsi que de 100 m à maximum nage. La cinématique, l'énergie et la puissance ont été évalués par des reconstitutions en 3D, bien que la consommation d'oxygène, les concentrations de lactate dans le sang et les mesures de force, respectivement. Les résultats ont montré qu'une plus grande production de force a été atteinte grâce à l'augmentation de la fréquence de la brassée et par conséquent, de la vitesse, qui demandait nécessairement une adaptation coordinative. Considérant que l'utilisation d'un tuba respiratoire n'a pas conduit à un traîne supplémentaire, les seuils ventilatoire anaérobie et métabolique (évaluées en utilisant des concentrations de lactate) ont révélé être proportionnels l'un à l'autre dans le crawl d'intensité modéré. La performance à cette intensité de nage n'a pas été expliquée par des paramètres généraux de brassée, par l'efficacité de propulsion et de performance, par la puissance métabolique et mécanique, mais donc en étant directement liée à la vitesse par une consommation maximale d'oxygène (domaine d'intensité sévère). Contrairement au domaine modéré, la performance de front crawl dans une intensité sévère a été partiellement décrite par la puissance de vaincre la traînée et l'efficacité de la performance. Dans l'intensité extrême en front crawl, les paramètres spatio-temporels ont été influencés par la fatigue induite et la contribution d'énergie, qui ont compté avec des participations aérobie et anaérobies similaires (lactique et alactique). En outre, à l'exception de la coordination, la fréquence et la longueur de la brassée, l'efficacité de la propulsion et les profils de coût d'énergie n'ont pas été discriminatives de la performance, mais une vitesse plus élevée a été obtenue, due à une supériorité

output de puissance, a une efficacité de propulsion et à une fréquence de brassée, en conduisant à un indice élevé de coordination.

Mots-clés: Natation, Front Crawl, Seuil, Efficacité, Puissance, Traînée, Énergie

List of Abbreviations

A	Oxygen uptake amplitude
AnAI	Anaerobic alactic
AnL	Anaerobic lactic
ANOVA	Analysis of variance
AnT	Anaerobic threshold
AnT _{met}	Metabolic AnT
AnT _{vent}	Ventilatory AnT
ATP	Adenosine Triphosphate
BxB	Breath-by-breath
C	Energy cost of locomotion
CI	Confidence interval
CM	Centre of mass
CO ₂	Carbon dioxide
CV	Coefficient of variation
D	Hydrodynamic drag force
E	Energy expenditure
\dot{E}	Metabolic power
F	Force
F _E CO ₂	Expiratory fraction of carbon dioxide
F _E O ₂	Expiratory fraction of oxygen
H ₂ O	Water
HR	Heart rate
IdC	Index of coordination
ICC	Intraclass correlation coefficient
IVV	Intracycle velocity variations
M	Mass
MAD-system	Measuring active drag system
n	Number of subjects
O ₂	Oxygen
PCr	Phosphocreatine
P _D	Power to overcome hydrodynamic resistance
P _o	Mechanical power output
r	Correlation coefficient
R	Respiratory exchange ratio
R ²	Determination coefficient
RMS	Root mean square

SD	Standard deviation
S _{full}	Swimming full body
S _{upper}	Swimming upper body
SL	Stroke length
SF	Stroke frequency
SPSS	Statistical package for the social sciences
STATA	Data analyses and statistical software
SV2	Snorkel with 2 valves
SV4	Snorkel with 4 valves
t	Time
v	Velocity
v _{AnT}	Velocity at anaerobic threshold
v@AnT _{met}	Velocity at metabolic anaerobic threshold
v@AnT _{vent}	Velocity at ventilatory anaerobic threshold
VCO ₂	Volume of carbon dioxide expired
V _E	Ventilation
V _{max}	Maximum velocity
V _{min}	Minimum velocity
VO ₂	Oxygen uptake
VO _{2basal}	Basal oxygen uptake
VO _{2max}	Maximal oxygen uptake
VO _{2peak}	Peak VO ₂
vVO _{2max}	Minimum velocity that elicits maximal oxygen uptake
V _T	Tidal volume
W _d	Work to overcome hydrodynamic resistance
W _{tot}	Total mechanical work
β	Energy equivalent for blood lactate accumulation
η _D	Performance (drag) efficiency
η _F	Froude efficiency
η _m	Mechanical efficiency
η _P	Propelling efficiency
τ	Time constant
2D	Two-dimensional
3D	Three-dimensional
[La ⁻]	Blood lactate concentrations
[La ⁻] _{max}	Maximal lactate concentration

Chapter 1 General Introduction

The aquatic environment is unique, with remarkable geology and vast resources, but while it is a suitable ecosystem for fauna and flora, its physical characteristics impose profound mechanical and physiological stresses on humans (Pendergast et al., 2015). In fact, the unnatural water complexities are a challenge to the real comprehension of human swimming locomotion (Pendergast and Lundgren, 2009), which depends on the generation of propulsive force and on the reduction of hydrodynamic drag. Thus, the capability to produce high propulsive force, while reducing the opposite drag, is decisive to achieve a certain swimming velocity (Toussaint and Beek, 1992). This velocity results from the stroke frequency (SF) and the distance the swimmer's body moves through the water in each cycle of the upper limbs, i.e., stroke length (SL), as represented in the following equation (Pendergast et al., 2006):

$$v = SF \times SL \quad (1)$$

Hence, velocity increase and/or decrease is determined by the SF and SL combination (Craig and Pendergast, 1979; Craig et al., 1985), characterised by a large variability that implies a highly individual process. Accordingly, this complex relationship between stroking parameters has often been reported as the swimmers' ability to swim efficiently (Barbosa et al., 2010a; Chollet et al., 1997; Seifert et al., 2007).

The action of the upper and lower limbs, as well as the trunk, varies during a swimming cycle, resulting in an intermittent application of propulsive force and drag that causes a not-constant instantaneous velocity (intracycle velocity variations; IVV). IVV are often considered as an indicator of efficiency and swimmer's technical level (Alberty et al., 2005; Figueiredo et al., 2013c; Vilas-Boas et al., 2010), contributing to the highly variable performance in swimming (Barbosa et al., 2010a; Figueiredo et al., 2012; Toussaint and Beek,

1992). In fact, IVV reflect the swimmer's ability to coordinate his/her propulsive forces, which is influenced by upper inter-limb coordination (Alberty et al., 2005; Figueiredo et al., 2013c; Gourgoulis et al., 2013; Schnitzler et al., 2008). This is traditionally assessed by the index of coordination (IdC) that is considered a useful tool to understand motor organization in swimming. The IdC quantifies the lag time between the propulsive actions of the two upper limbs, expressed as the percentage of the overall duration of the front crawl cycle, and can shift from catch-up (IdC < 0%) to opposition (IdC = 0%) and superposition (IdC > 0%) modes (Chollet et al., 2000; Seifert et al., 2004). So, although the IdC value by itself does not indicate the motor skill of the swimmer, it can be used as an indicator of performance or efficiency (Seifert, 2010).

All the above-referred parameters influence swimming velocity (Barbosa et al., 2010a; Figueiredo et al., 2013a; Seifert et al., 2004) that depends on the swimmers metabolic expenditure (E) (Barbosa et al., 2006; Pendergast et al., 2006; Pyne and Sharp, 2014):

$$v = E/C \quad (2)$$

E should be computed based on measures/estimates of the aerobic and anaerobic energy contributions (Fernandes et al., 2006; Sousa et al., 2014b; Vilas-Boas and Santos, 1994) and energy cost (C) is the amount of metabolic energy spent to cover one unit of distance (m). This metabolic energy depends on the overall efficiency (η_o), the propelling efficiency (η_p) and the mechanical work to overcome hydrodynamic resistance (W_d) (Barbosa et al., 2010a; Figueiredo et al., 2011; Zamparo et al., 2014):

$$C = W_d/(\eta_p \times \eta_o) \quad (3)$$

W_d is evaluated by using different active drag assessment methods, but the one most adequate is still a controversial issue (Havriluk, 2007; Seifert et al., 2015; Toussaint et al., 2004). The η_o reflects the portion of metabolic power that is

converted to mechanical power since, in this transformation process, part of the chemical power present in the foodstuff is used for thermoregulation and, so, η_o is quantified by the ratio of mechanical power output (P_o) to metabolic power input (\dot{E}) (Toussaint and Hollander, 1994; Zamparo, 2011):

$$\eta_o = P_o / \dot{E} \quad (4)$$

Unlike on land, water does not allow for a solid push-off, forcing swimmers to give water a velocity change, which implies that it acquires kinetic energy. The efficiency with which \dot{E} is transformed into useful power to overcome drag that contributes to thrust (P_D) is given by performance (drag) efficiency (η_D) (Toussaint et al., 1988b; Zamparo and Swaine, 2012):

$$\eta_D = P_D / \dot{E} \quad (5)$$

Taking into account the above-referred theoretical assumptions, it is recognized that swimming locomotion depends on the interplay between biomechanical and energetic factors (Fernandes, 2006; Figueiredo, 2011; Vilas-Boas, 1993). Thus, to comprehend the swimming determinants as a function of different swimming intensities, it is necessary to analyse the biophysics of swimming locomotion, which means relating biomechanical and energetic constraints and its influence on performance. In fact, the biophysical determinants related to swimming performance are one of the most attractive topics within the swimming science community, being consensual that the biophysical approaches are an element to enhance performance and achieve high-standard levels in competitive swimming (Barbosa et al., 2010a; Vilas-Boas, 2010). However, few studies have related the above-referred swimming performance factors, enabling a deeper and integrative knowledge.

Among the different forms of locomotion in swimming, the front crawl technique is the one that allows for the highest swimming velocity and is considered the most economic conventional swimming technique due to its biomechanical

characteristics (Barbosa et al., 2006; Holmer, 1974; Lavoie and Montpetit, 1986). Hence, as a consequence of its use in freestyle events in official competitions (six competitive distances in contrast to the three events in each of the remaining techniques) and, particularly, in the most important one – the 100 m freestyle -, front crawl is the most widely used form of swimming locomotion in training as well as in research. The purpose of this Thesis was to identify and characterise biophysical performance determinants of the front crawl at different swimming intensities, going from low/moderate intensities until extreme exertion.

In the current Chapter - the General Introduction - we contextualise the theoretical assumptions regarding front crawl locomotion and then, in Chapters 2 to 8, the experimental accomplishments of the current work are presented. Afterwards, it is elaborated a general discussion upon the results obtained from our experimental studies with the reports of the specialized literature (Chapter 9). Finally, the main conclusions, suggestions for future research and bibliographic references are presented in Chapters 10, 11 and 12 (respectively). A more detailed description of the experimental studies will now be addressed.

Swimming performance corresponds to the time required to cover a specific distance, being a consequence of the average changes in instantaneous velocity that results from the intermittent application of forces (resistive and propulsive) acting on the swimmer's body. IVV is commonly assessed by measuring the velocity of a fixed point (usually the hip) or the centre of mass (CM) reconstruction. Although the use of the CM is considered more valid (Barbosa et al., 2003; Psycharakis et al., 2010; Psycharakis and Sanders, 2009), the IVV assessment of the hip is frequently used due to the quickness in data collection and analyses (Gourgoulis et al., 2013; Schnitzler et al., 2010; Vilas-Boas et al., 2010). Nevertheless, there is an associated error of using a fixed body point to assess IVV that should be considered. Following this reasoning, we have conducted a methodological study (**Appendix I**) to guide our subsequent work, in which the front crawl kinematic profiles of the hip and

the CM were compared, with respect to displacement and forward velocity, and the error magnitude of using a fixed body point to assess IVV was quantified.

As increases in the instantaneous velocity occur when the propulsive force of the swimmer exceeds the drag, the capability to produce high propulsive force, while reducing the opposite drag, is decisive to attain a certain swimming velocity (Barbosa et al., 2010a; Toussaint et al., 1988a). Hence, the swimming propulsive force is considered a main performance determinant, but the relationship between the biomechanical parameters and the effective ability to produce muscular force lacks experimental evidence. By assessing biomechanical parameters using a fixed point as reference (**Appendix I**), it was proposed to examine the relationships between velocity, stroking parameters (SF and SL), η_p , IVV, IdC, and force production in low to extreme front crawl swimming intensities (**Chapter 2**). Swimmers performed front crawl using only the upper limbs both on the system to measure active drag force (giving the mean propulsive force) as well as in free-swimming conditions. It was expected that high force production required increases in velocity, stroking parameters and η_p . Moreover an optimal coordination pattern enabling continuity of propulsive phases and lower IVV was also supposed.

Concurrently with the biomechanical factors, also the energetic parameters, representing the alactic, anaerobic-lactic and aerobic systems, play an important role in swimming performance (Figueiredo et al., 2011; Pendergast et al., 2006; Toussaint and Hollander, 1994). The aerobic energy source, assessed through the oxygen uptake (VO_2) was difficult to measure due to technical constraints imposed by the swimming pool and the aquatic environment (Toussaint et al., 1988a). Nevertheless as technology advanced, new equipment has been used to assess VO_2 in swimming, helping research to progress. Following this evidence, it was conducted a complementary study to analyse if a new optimized breath-by-breath snorkel is valid for VO_2 assessment in ecological swimming conditions, particularly analysing if it is proper for VO_2 assessment (**Appendix II**).

Then, hypothesising that ventilatory data validity could be compromised if swimmers experience an additional hydrodynamic drag when using respiratory snorkel when front crawl swimming, as well as during the gliding after starting and turning, it was tested for drag and analysed the eventual ecological disturbance during turns (**Chapter 3**). It was expected that swimming with this snorkel would not lead to additional drag, independently of the exercise intensity. However, as was not possible to use the turning technique performed in competition and in training, it was expected that an evident increase in turning time would occur when, alternatively, performing the open turn.

By the same previous token, the swimmers physiological evaluation is an essential tool to increase the efficiency of the training processes, identify the different swimming intensities and to predict performance (Olbrecht, 2000; Pyne et al., 2001; Smith et al., 2002). The popularity of anaerobic threshold (AnT) as the highest sustainable exercise intensity, at which the balance between production and removal of blood lactate remains constant, as performance indicator, has increased dramatically. Nowadays, many laboratories are routinely measuring it as an integral component of the physiological assessment of aerobic capacity, which has been suggested as the best indicator of endurance swimming performance (Fernandes et al., 2010; Olbrecht, 2000; Smith et al., 2002), due to the difficulty of implementing $\dot{V}O_2$ measurements. In this sense, accurately identifying AnT corresponding velocity (v_{AnT}) plays an important role in prescribing appropriate swimming exercise intensity, as well individualizing training process. As AnT has been commonly described by standardized references either to a metabolic change in $[La^-]$ (metabolic anaerobic threshold; AnT_{Met}) and ventilatory gas exchange data (ventilatory anaerobic threshold; AnT_{Vent}) we aimed to assess and characterize both AnT_{Met} and AnT_{Vent} expecting that AnT_{Vent} and AnT_{Met} could be directly proportional to each other (**Chapter 4**).

Together with the v_{AnT} , also the minimum velocity that elicits $\dot{V}O_2$ ($\dot{V}O_{2max}$) has been identified as swimming performance indicator (Costill et al., 1992;

Fernandes et al., 2008; Sousa et al., 2014b), with some studies focusing on the identification of biomechanical and energetic performance determinants both at vAnT (Figueiredo et al., 2014; Oliveira et al., 2012; Psycharakis et al., 2008) and $\dot{V}O_{2\max}$ (Fernandes et al., 2006; Fernandes et al., 2008; Sousa et al., 2014b). As these previous studies examined the vAnT and $\dot{V}O_{2\max}$ biomechanical and energetic determinants independently, the current analysis aimed to go further since swimming performance is biophysically based (Barbosa et al., 2010a; Pendergast et al., 2006). So, in **Chapter 5** it was conducted a biophysical approach, combining the biomechanical parameters (this time introducing 3D measurements to complement 2D procedures) with the biomechanical ones, to identify which factors better explain the variation in the vAnT and $\dot{V}O_{2\max}$. It would be expected a direct relationship between stroking parameters, efficiency, coordination, mechanical and metabolic power and vAnT and $\dot{V}O_{2\max}$.

Improvement of swimming performance at moderate and severe intensity domains (expressed by vAnT and $\dot{V}O_{2\max}$, respectively) could be the base for the velocity increment in the extreme intensity where the majority of competitive events is situated (Maglischo, 2003; Olbrecht, 2000). In extreme exercise domain, performance could be compromised as a consequence of the specific fatigue of these efforts (Bonifazi et al., 1993; Fitts, 1994), consequently affecting biomechanical parameters and influencing both velocity and energetics (Alberty et al., 2005; Craig et al., 1985; Figueiredo et al., 2013b; Psycharakis and Sanders, 2008; Soares et al., 2014). Therefore, in **Chapter 6**, we particularly investigated the spatiotemporal parameter changes during the 100 m front crawl event, which well represents swimming performance at the extreme intensity domain (effort of ~1 min duration). For that purpose, the protocol was monitored through 3D dual-media automatic tracking (for the first time in swimming science research as an attempt to obtain faster and eventual less erroneous 3D reconstructions) to analyse 3D upper limb-pattern, expecting that it would change with the increase of fatigue.

For short-duration events conducted in the extreme domain, the total amount of E liberated is the sum of the integrated rates of oxidative metabolism, anaerobic glycolysis (leading to lactic acid production) and creatine phosphate splitting. Not taking into account all the energy sources will result in an underestimation of E, negatively affecting the understanding of performance at short competitive events (Zamparo et al., 2011). Recently, it has been suggested that, even for short duration swimming efforts, there is a relevant aerobic energy contribution (Figueiredo et al., 2011; Peyrebrune et al., 2014), establishing the importance of $\dot{V}O_2$ kinetics analysis (by modelling the $\dot{V}O_2$ response). Hence, the purpose of **Chapter 7** was to complement the previous biomechanical findings (**Chapter 6**) by particularly assessing the $\dot{V}O_2$ kinetics, the different energy systems contribution and C at extreme swimming intensity domain. Considering that $\dot{V}O_2$ kinetics is influenced by differences in active muscle mass (that have a potential effect in the overall bioenergetics responses), it was complementarily compared 100 m full body with performing only with upper body. The expectation was that the amount of active muscle mass would increase the metabolic demand and, consequently, C.

After identifying the biomechanical and bioenergetical front crawl determinants, it was important to know how to enhance performance by manipulating these parameters (Barbosa et al., 2010b). In this sense, following the same line of the previous exploratory research, and extending the aforementioned biophysical analysis (**Chapter 5**) to the extreme intensity domain, it was examined how cohort groups of swimmers organised selected biomechanical (SF, SL, η_P and power) energetic (C) and coordinative (IdC) factors throughout 100 m front crawl performed at maximal exertion (**Chapter 8**). It was expected a distinct profile and magnitude of the selected variables, during the effort, according to the performance level.

Chapter 2

Biomechanical determinants of force production in front crawl swimming.

João Ribeiro¹, Kelly de Jesus¹, Pedro Figueiredo^{1,2}, Huub Toussaint³, Laura Guidetti⁴, Francisco Alves⁵, João P. Vilas-Boas^{1,6}, Ricardo J. Fernandes^{1,6}.

¹ Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal

² Higher Education Institute of Maia, Maia, Portugal

³ Amsterdam University of Applied Sciences, School of Sports and Nutrition, Amsterdam, Netherlands

⁴ Health Sciences Department, University of Rome “Foro Italico”, Rome, Italy

⁵ Faculty of Human Movement, Technical University of Lisbon, Lisbon, Portugal

⁶ Porto Biomechanics Laboratory, University of Porto, Porto, Portugal

Published on Journal of Sports Medicine and Physical Fitness (2013), 53 (1-3), 30-37.

Abstract

Swimming propulsive force is a main performance determinant that has been related to some biomechanical parameters. Nevertheless, as the link among those parameters and force production remains unclear, it was aimed to examine the relationships between the stroking parameters, intracycle velocity variations, arm coordination, propelling efficiency and force production in front crawl swimming. Ten trained swimmers performed two repetitions of an intermittent graded velocity protocol using arms-only front crawl technique (one on the system to measure active drag force, which gives us the mean propulsive force, and other in free-swimming conditions), consisting in 10 bouts of 25 m from slow to maximal velocity. The tests were videotaped in the sagittal plane (2D kinematical analysis) and video images were digitized enabling the stroking parameters (velocity, stroke frequency and stroke length), intracycle velocity variations, index of coordination and propelling efficiency assessment. Force presented a direct relationship with velocity, stroke frequency and index of coordination ($r = 0.86, 0.82, 0.61$, respectively, $p < 0.05$) and an inverse relationship with stroke length, intracyclic velocity variations and propelling efficiency ($r = -0.66, -0.57, 0.60$, respectively, $p < 0.05$). The relationships between force and velocity, and between force and intracyclic velocity variations, were best expressed by a power regression model ($F = 18.01v^{2.5}$ and $F = 3.00IVV^{-1.50}$, respectively). A quadratic regression was the most appropriated model for expressing the relationships between force and stroke frequency ($F = -57.10SF^2 + 220.98SF - 105.04$), index of coordination ($F = 45.45IdC^2 + 2.10IdC + 0.05$) and propelling efficiency ($F = 328.62\eta_P^2 - 1350.212\eta_P + 1536.46$). High stroke frequency, optimal coordination and low intracyclic velocity variations seem to be required to produce high force values in front crawl swimming. By knowing how to manipulate those variables, both in training and competition conditions, swimmers would be able to increase their force production.

Key words: biomechanics, force, motor control, velocity, swimming.

Introduction

Swimming velocity depends on the generation of propulsive force necessary to match the hydrodynamic drag produced by the moving body. So, the capability to produce high propulsive force, while reducing the opposite drag, is decisive to achieve a certain velocity (Barbosa et al., 2010; Toussaint et al., 1988). Since velocity is a product of stroke frequency (SF) and stroke length (SL), and its increase (or decrease) is determined by SF and SL combinations (Craig and Pendergast, 1979; Figueiredo et al., 2013b), the relationship between these parameters is one of the major points of interest in swimming training and research (Barbosa et al., 2010; Fernandes et al., 2005). Nevertheless, the complex relationships between those stroke characteristics have been often reported as the swimmers' ability to swim with high efficiency, emphasizing the swimming technique rather than the propulsive force production. In fact, the relationship between stroking parameters and the effective ability to produce muscular force (to execute the stroke cycles) lacks experimental evidence.

The action of the arms, legs and trunk varies, during a stroke cycle, resulting in an intermittent application of force and, therefore, in intracycle velocity variations (IVV; D' Acquisto & Costill, 1998) that are responsible for average velocity degradation (Figueiredo et al., 2012). The IVV have also been reported as a relevant swimming performance determinant since, for a finite energy supply, the best solution to optimize performance is to reduce its magnitude and increase the capacity to produce propulsive force (Figueiredo et al., 2013b). Increases in IVV imply greater mechanical work demand and, theoretically, changes of 10% in the swimming velocity within a stroke cycle results in an additional work of about 3% (Nigg, 1983). Therefore, IVV should give an indication of swimming efficiency and swimmer's technical level (Seifert et al., 2010).

Complementarily, it is known that IVV are influenced by inter-arm coordination (Seifert et al., 2010; Schnitzler et al., 2009), traditionally assessed by the index

of coordination - IdC - that quantifies the lag time between the propulsive actions of the two arms. It was observed previously that when during increasing swim paces a change from catch-up to superposition has been adopted by elite swimmers to maintain continuity between the propulsive phases (Seifert et al., 2010), meaning that using a best coordination solution, swimmers should be able to reduce IVV and optimize propulsion (Figueiredo et al., 2012; Figueiredo et al., 2013b).

Nonetheless, the propulsion continuity in swimming could not be automatically related to greater propulsion generation, since it depends on the correct orientation and velocity of the body segments. Thus, the capability to generate effective propulsion reflects the swimmers' propelling efficiency, and despite it has been considered as a swimming performance determinant, and discriminative of technical level (Toussaint et al., 1990), its relationship with force production has not yet been clarified. The purpose of this study was to examine the relationships between stroking parameters, IVV, arm coordination, propelling efficiency and force production in front crawl swimming.

Material and Methods

Participants

Ten trained male swimmers volunteered to participate in the present study. Their main physical characteristics, training background and performance are as follows: 18.96 ± 2.56 years, height: 1.80 ± 0.65 m, body mass: 72.46 ± 4.33 kg, years of training background: 13.57 ± 3.08 , percentage of the 100 m world record: $89.57 \pm 15.91\%$. Participants were previously familiarized with the test procedures and the equipment used in the experiment. All participants provided informed written consent before data collection, which was approved by the local ethics committee. All experiments were conducted according to the Declaration of Helsinki.

Experimental procedure

The test session took place in a 25 m indoor pool, 1.90 m deep, with a water temperature of 27.5 °C. A warm-up of low to moderate swimming intensity was conducted, both in free swimming and on a system to measure active drag force (MAD-system; Toussaint et al., 1990). Briefly, each subject performed two sets of an intermittent graded velocity protocol consisting in 10 bouts of 25 m front crawl using only the arms (with the legs elevated and constrained by a pull buoy), with 3 min rest in-between, from slow to maximal velocity: one set was conducted on the MAD-system and the other in free-swimming conditions, with a 24 h interval. Each bout was self-paced to avoid the velocity variations that can arise when the swimmer follows a target (Seifert et al., 2010). The swimmers were randomly assigned to start the testing by performing on the MAD-system or swimming freely. Each subject swam alone, avoiding pacing or drafting effects.

MAD system

The MAD-system required the swimmer to directly push-off fixed pads attached to a 23 m rod, which was fixed 0.8 m below water surface, and had a standard distance of 1.35 m between each pad (Figure1, left panel). The rod was instrumented with a force transducer allowing measurement of push-off force from each pad (Figure 1, right panel).

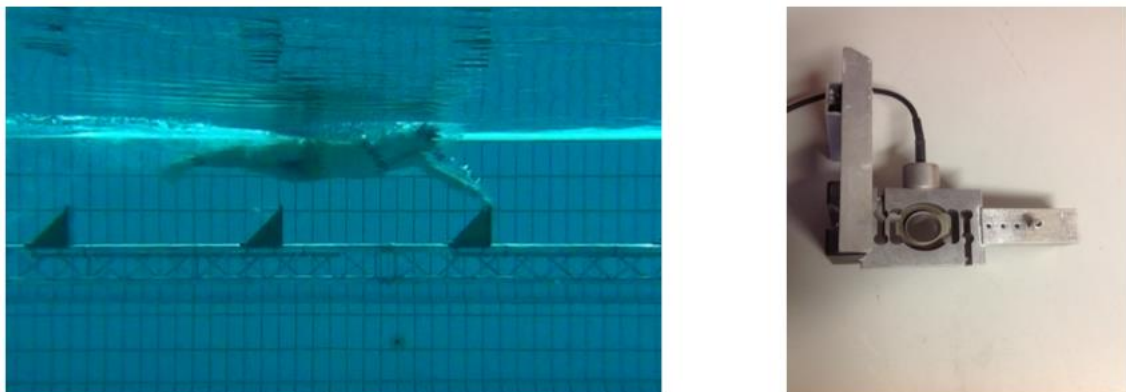


Figure 1. System to measure active drag (MAD-system, left panel) and respective force transducer (right panel).

The force signal were acquired by an A/D converter (BIOPAC Systems, Inc., Goleta, CA, USA) at a sample rate of 500 Hz and filtered with a low pass digital filter with a cut-off frequency of 10 Hz. Assuming a constant swimming velocity, the mean force equals the mean drag force and, hence, the 10 velocity/force ratio data were least square fitted according to Equation 1:

$$D = A.v^n \quad (1)$$

where D is active drag force, A and n are parameters of the power function and v is the swimming velocity. For each subject A and n were estimated using Equation (1) (Matlab version R2012a, Mathworks, Inc., Natick, MA, USA) with a Levenberg-Marquardt algorithm (Toussaint et al., 1988; Toussaint et al., 2004).

Biomechanical parameters

Swimmers were videotaped in the sagittal plane (for 2D kinematical analysis) using an underwater camera (Sony® DCR-HC42E, 1/250 digital shutter, Nagoya, Japan) kept at 0.30 m depth (Sony® SPK-HCB waterproof box, Tokyo, Japan) and at 6.78 m from the plane of movement, as previously described (Fernandes et al., 2012). Subjects were monitored when passing through a specific pre-calibrated space using two-dimensional rigid calibration structure (6.30 m²) with six control points. The video images were digitized using Ariel Performance Analysis System (Ariel Dynamics, San Diego, USA) at a frequency of 50 Hz, considering five anatomical reference points: humeral heads, ulnohumeral joints, radiocarpal joints, 3rd dactylions and trochanter major. A 2D reconstruction was accomplished using Direct Linear Transformation algorithm and a low pass digital filter of 5 Hz.

SF was assessed by the inverse of the time needed to complete one stroke cycle and SL by the horizontal displacement of the left hip. The mean velocity was computed by dividing the swimmers' average hip horizontal displacement by the time required to complete one stroke cycle. The IVV was calculated

through the coefficient of variation of the velocity to time mean values (Equation 2) (Figueiredo et al., 2012):

$$CV = SD.mean^{-1} \quad (2)$$

where CV is the coefficient of variation and SD the standard deviation of velocity values.

Arm coordination was quantified using the IdC, measuring the time duration between the final of the propulsive action of one arm and the beginning of the propulsion of the other, and expressed as percentage of the overall duration of the stroke cycle (Chollet et al., 2000). The propulsive phase was considered to begin with the start of the backward movement of the hand until the moment where it exits from the water (pull and push phases), and the non-propulsive phase initiates with the hand water release and ends at the beginning of the propulsive phase (recovery, entry and catch phases). For the front crawl technique, three coordination modes were proposed (Chollet et al., 2000): (i) catch-up, when a lag time occurred between the propulsive phases of the two arms (index of coordination < 0%); (ii) opposition, when the propulsive phase of one arm started when the other arm ended its propulsive phase (index of coordination = 0%) and (iii) superposition, when the propulsive phases of the two arms are overlapped (index of coordination > 0%).

The propelling efficiency (η_p) of the arm stroke was estimated by assessing the underwater phase only, according to Equation 3 (Zamparo et al., 2005):

$$n_p = \left(\frac{v}{2} \cdot \pi \cdot SF \cdot L \right) \cdot (2/\pi) \quad (3)$$

being v the mean velocity of the swimmer, SF the stroke frequency (in Hz) and L the average shoulder to hand distance (assessed trigonometrically by measuring the upper limb length and the average elbow angle during the

insweep of the arm pull). The equation was not adapted for the contribution of the legs (as originally proposed) as swimmers performed with arms only.

Statistical analysis

The normality of distribution was checked using the Shapiro-Wilk test. Descriptive statistics (mean, range and standard deviation) from all measured variables were calculated. A two-way ANOVA was used to compare the normalized velocity and SF in free swimming and MAD-system conditions, and the effect of bouts of 25 m on the different variables was analysed through the one-way ANOVA repeated measures. The relationships among variables were assessed by Pearson's correlation test and regression analysis (using second degree polynomial, linear, exponential, power or logarithm regression models). For the exponential and power regressions the coordination data were normalized between 0 and 1, as follows (Equation 4):

$$1 - [(30 - IdC)/60] \quad (4)$$

Then, the model was created by averaging the individual coefficients and the regression model was selected in function of the error of each individual and the average equation. These statistical analyses were performed using IBM® SPSS Statistics and the level of significance was set at 5%.

Results

A non-significant difference ($3.42 \pm 0.93\%$) was observed for normalized velocity between free and MAD-system conditions, while a statistical difference of $19.57 \pm 5.78\%$ ($F_{8,162} = 380.76$, $p < 0.05$) was noted between normalized SF (Figure 2).

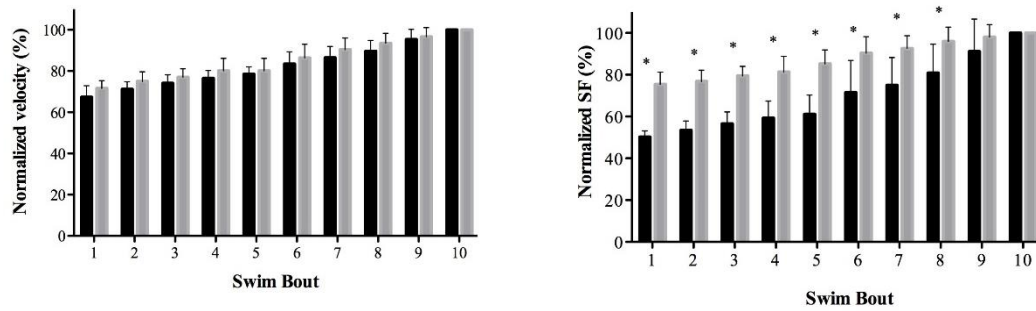


Figure 2. Comparison between free swimming (black) and MAD-system (gray) conditions for the normalized velocity (left panel) and the normalized stroke frequency (SF, right panel) at each velocity. * Significant difference between the two conditions, $P < 0.05$.

For the 10 bouts of free swimming, the ANOVA indicated an increase of velocity ($F_{9.81} = 80.56$, $p < 0.05$), SF ($F_{9.81} = 30.20$, $p < 0.05$), IdC ($F_{9.81} = 9.64$, $p < 0.05$) and force ($F_{9.81} = 50.27$, $p < 0.05$), and decrease of SL ($F_{9.81} = 17.55$, $p < 0.05$), IVV ($F_{9.81} = 4.14$, $p < 0.05$) and η_P ($F_{9.81} = 11.94$, $p < 0.05$). The results of the Person's correlation, among all variable, are presented in Table 1.

Table 1. Correlations coefficients among the studied variables. Significant correlation (r) at $P < 0.05$.

	Velocity	SF	SL	IVV	IdC	η_P
Force	0.86	0.82	-0.66	-0.57	0.61	-0.60
Velocity		0.84	-0.57	-0.62	0.56	-0.48
SF			-0.84	-0.57	0.71	-0.77
SL				0.50	-0.69	0.86
IVV					-0.48	0.46
IdC						-0.74

SF= Stroke frequency; SL= Stroke length; IVV= Intracyclic velocity variations; IdC= Index of coordination; η_P = Propelling efficiency

As the swimmers increased force production, the velocity ($r = 0.86$, $p < 0.05$), SF ($r = 0.82$, $p < 0.05$) and IdC ($r = 0.61$, $p < 0.05$) increased, and SL ($r = -0.66$, $p < 0.05$), IVV ($r = -0.57$, $p < 0.05$) and η_P ($r = -0.60$, $p < 0.05$) decreased.

From the five tested regressions models, two were found as the most appropriated, both for individual (Table 2) and polled analysis (Figure 3). The relationship between force and velocity and IVV showed that a power

regression was the most appropriate fit and, on the other hand, a quadratic regression was found as the best model between force and SF, SL, IdC and η_p .

Table 2. Regression modelling between force (F) and velocity (v), stroke frequency (SF), stroke length (SL), intracyclic velocity variations (IVV), index of coordination (IdC) and propelling efficiency (η_p).

Regression	Equation	Mean Error	SD Error	Min<Error<Max	Min<R ² <Max	Mean R ²
Power	$F=18.01v^{2.5}$	0.09	0.03	0.01<Error<1.04	0.98<R ² <1	0.99
Quadratic	$F=-57.10SF^2+220.98SF-105.04$	0.23	0.19	0.01<Error<1.87	0.83<R ² <0.97	0.94
Quadratic	$F=338.62SL^2-250.55SL+51.18$	0.32	0.23	0.02<Error<1.98	0.78<R ² <0.92	0.87
Power	$F=3.00IVV^{-1.50}$	0.34	0.26	0.09<Error<2.11	0.43<R ² <0.90	0.63
Quadratic	$F=45.45IdC^2+2.10IdC+0.05$	0.21	0.19	0.05<Error<1.78	0.45<R ² <0.95	0.71
Quadratic	$F=328.62\eta_p^2-1350.212\eta_p+1536.46$	0.20	0.17	0.03<Error<1.55	0.68<R ² <0.96	0.81

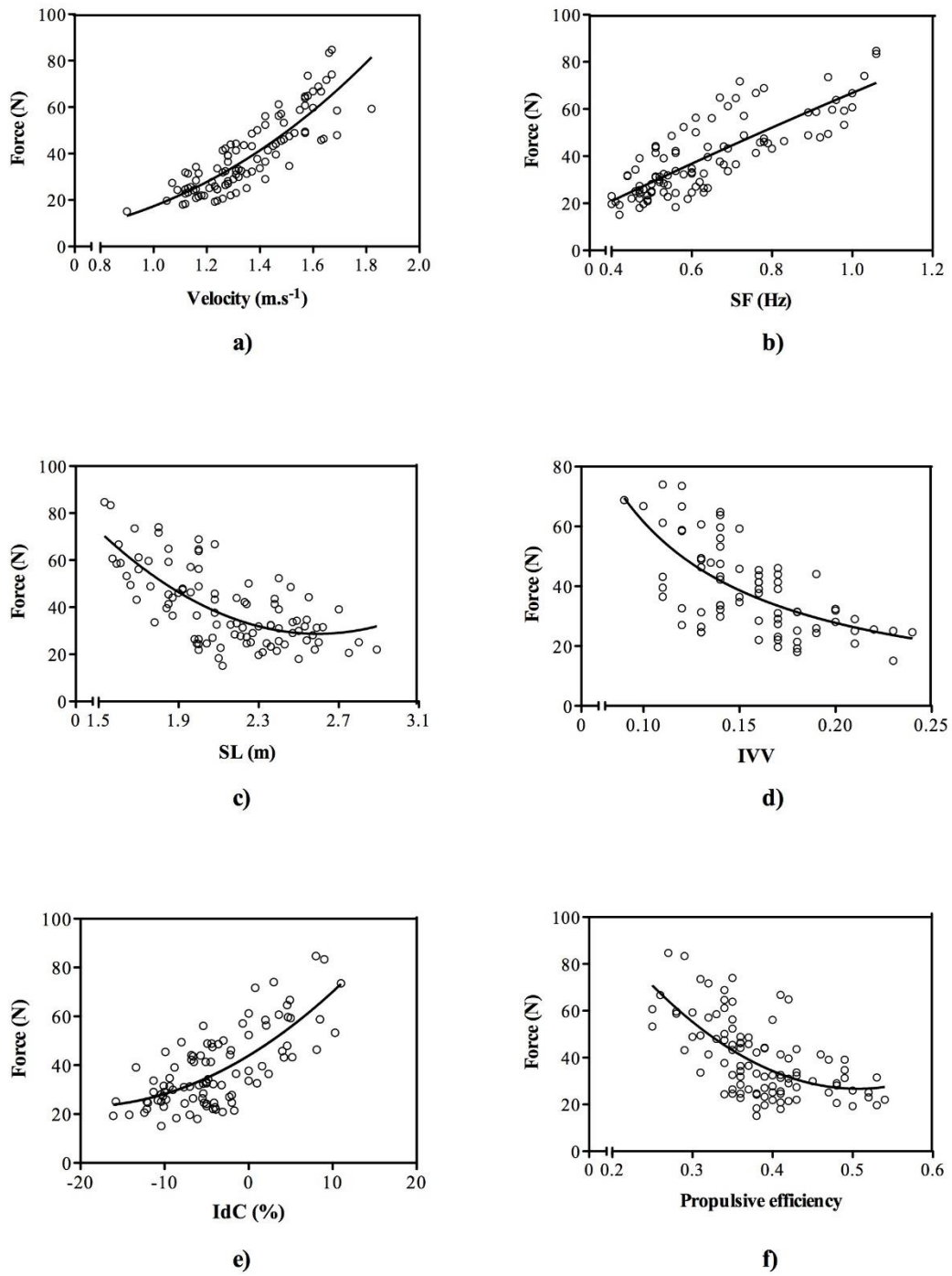


Figure 3. Relationship between force and velocity (a), stroke frequency (b) stroke length (c), intracyclic velocity variations (d), index of coordination (e) and propelling efficiency (f) average for the ten swimmers.

Discussion

Force production in front crawl swimming has been considered as a main performance determinant, but its relationship with the most relevant biomechanical parameters lacks experimental evidence. The aim of the present study was to examine the relationships between force and stroking parameters (velocity, SF and SL), IVV, IdC and η_P , in front crawl swimming. The main findings of the present study were that high force production requires increases in SF and, consequently, in velocity. Coordination adaptations permitted high force outputs due to continuity of propulsive phases and, concomitantly, IVV decreases, avoiding velocity degradation. The linkage between force and SF, SL, IdC and η_P showed a quadratic dependence and a power regression model was found between force and velocity and IVV.

In the present study, the assessed mean values of propulsive forces were assumed to be equal to the mean drag forces obtained from measurements on MAD-system (Berger et al., 1999), once, for a constant velocity the mean propulsive force should be equal to the mean drag force acting on the body of the swimmer (Toussaint et al., 1988; Toussaint et al., 2004). In addition, the maximal force production in free swimming would be similar to the recorded force production when swimming on the MAD-system, a fact that was confirmed by the normalized velocity. Nevertheless, the normalized SF changed between the two conditions, being higher on the MAD-system due to the fixed SL, as previously described (Seifert et al., 2010).

Concerning the stroking parameters, the correlation between force and velocity was positive and a quadratic dependence was observed. These data are in agreement with the literature (Martin et al., 1981; Toussaint et al., 1988; Toussaint et al., 2004), evidencing the importance of swimming velocity on force production, particularly with increasing velocity. Moreover, force produced by the swimmers showed to be positively influenced by SF increases, confirming previous investigations (Cabri et al., 1988; Martin et al., 1981) and

consequently, lower SL (Barbosa et al., 2010). The quadratic linkage between force and these variables could be explained by the fact that, at early protocol stages (lower values of velocity), force production might mostly be due to the fast increase in SF, and consequent decrease in SL. After that, the increase in force production might be more dependent on combination of a slightly additional increase of SF and a vaguely maintenance of SL, similar to the reported relation of these parameters with swimming velocity (Barbosa et al., 2010).

The inverse relationship of force and IVV highlighted the importance of propulsive continuity to achieve higher values of force production (Figueiredo et al., 2013b), and their non-linear relationship could be explained by the fact that the neuromuscular activation of several muscles in a multi-segment and multi-joint movement follows the curvilinear force - velocity relationship pattern for a single joint system (Minetti, 2000). Such increase of propulsive continuity was concomitant with the rise of IdC values, presenting a quadratic relationship with force (Seifert et al., 2009), corroborating that to produce higher force values swimmers modify their arm stroke. These changes in arm coordination reflect changes on reduction of relative duration of the non-propulsive phases that, consequently, lead to changes on SF and SL (Chollet et al., 2000; Figueiredo et al., 2013a; Seifert et al., 2007). This coordination, and consequent stroking parameters adaptations, might be interpreted as a response of the swimmer to produce force, demonstrating that its production is directly dependent on motor control and optimal coordination pattern, as a response to the imposed constraints (e.g. hydrodynamic drag; Seifert et al., 2009).

The IdC changes enabled continuity between the propulsive phases, but this did not necessarily mean higher propulsion generation values since swimmers could slipped through the water. This fact could be explained by the observed inverse relationship, and negative quadratic dependence of force on η_P . A greater propelling efficiency is traditionally associated with a better capacity to produce force (Barbosa et al., 2010; Toussaint et al., 2006), but, since a high

SF is required to generate force and η_P was inversely related to SF, consequently a reduction of the propulsion effectiveness has occurred.

Conclusions

Optimization of force production required increases in SF and, consequently, in swimming velocity. Optimal coordination adaptations, enabling continuity of propulsive phases and IVV decreases were essential to produce higher values of force. However, these adaptations did not necessarily guarantee propulsion efficiency as observed by SL and η_P decrease. Hence, the manipulation of the biomechanical variables might be one of the factors through which swimming force could be altered, emphasising the need of its evaluation, identification and intervention as a common practice both in swimming training and competition.

Chapter 3

AquaTrainer® snorkel does not increase hydrodynamic drag but influences turning time.

João Ribeiro^{1,2}, Pedro Figueiredo^{1,3}, Laura Guidetti⁴, Francisco Alves⁵, Huub Toussaint⁶, João Paulo Vilas-Boas^{1,2}, Carlo Baldari⁴, Ricardo J. Fernandes^{1,2}

¹ Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal;

² Porto Biomechanics Laboratory, University of Porto, Porto, Portugal.

³ School of Physical Education, Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

⁴ Department of Movement, Human and Health Sciences University of Rome "Foro Italico", Rome, Italy.

⁵ Faculty of Human Movement Technical University of Lisbon, Lisbon, Portugal

⁶ Amsterdam University of Applied Sciences, School of Sports and Nutrition, Amsterdam, Netherlands.

Published on International Journal of Sports Medicine DOI: 10.1055/s-0035-1555859.

Abstract

Our purpose was to verify if the use of the new AquaTrainer® respiratory snorkel lead to an increase of front crawl hydrodynamic drag and if the constraint of using an adapted turning technique influences its corresponding turning time. Twelve swimmers performed two (without and with snorkel) 12x25 front crawl repetitions from low to maximal velocity on the measuring active drag system. Complementarily, three swimming turns were compared: open turn with snorkel, tumble turn and open turn without snorkel. Drag values were similar without vs with snorkel at 0.9, 1.1, 1.3, 1.5 and 1.7 m.s⁻¹ velocities: 15.84 ± 5.32 vs 16.18 ± 4.81, 25.60 ± 6.69 vs 26.03 ± 6.17, 38.37 ± 8.04 vs 38.88 ± 7.56, 54.64±10.06 vs 55.08±9.55, 74.77±14.09 vs 74.92±13.14 N, (respectively, p≥0.05), and high agreement between conditions was observed (p<0.01). Front crawl swimming with snorkel using the open turn implied an increase in turning time of 14.2 and 5.1% than the tumble turn and open turn without the apparatus (p<0.01). AquaTrainer® snorkel does not lead to an increase active drag during front crawl performed at a large range of velocities and, consequently, the metabolic energy necessary to overcome total drag when will not be affected. However, turning with it requires an additional time that should be taken into account in scientific research and training conditions.

Key words: swimming, energetics, K4b², turns, front crawl

Introduction

Oxygen consumption ($\dot{V}O_2$) is frequently used to evaluate swimming energetics, particularly by assessing relevant related parameters like $\dot{V}O_{2max}$, time to exhaustion at $\dot{V}O_{2max}$, $\dot{V}O_2$ kinetics, energy expenditure and energy cost (for a detailed and actual review see Sousa et al., 2014a). For this purpose, commercially available snorkels are used for respiratory gas collections, both adapted for swimming flume and swimming pool conditions. However, by using this apparatus, ventilatory data validity could be compromised if subjects experience an additional hydrodynamic drag during swimming, as well as during the passive glide phases after starting and turning. This is clearly evidenced by the strong relationship between the energy cost and the mechanical work to overcome drag (Pendergast et al., 2006).

Swimming snorkel additional hydrodynamic drag was tested before, but neither the first apparatus produced for $\dot{V}O_2$ measurements in swimming (Toussaint et al., 1987) nor that designed following strict hydrodynamic concerns (Dal Monte et al., 1994) evidenced substantial differences comparing with unimpeded swimming. In addition, no alterations of the front crawl kinematics (Kjendlie et al., 2003) and swimming efficiency (Barbosa et al., 2010) were reported when wearing a modified version of the Toussaint's snorkel (Toussaint et al., 1987) and the AquaTrainer® (first version) snorkel, respectively. Furthermore, other snorkel models and/or upgrades were considered suitable for $\dot{V}O_2$ assessment during swimming (Keskinen et al., 2002; Keskinen et al., 2003; Rodriguez et al., 2008), although additional drag and/or technical modifications were not tested. In fact biomechanical modifications when using a respiratory snorkel were only proposed for breaststroke, but hydrodynamics was not analyzed Conceição et al., 2013).

Despite the apparent inexistence of increased drag when front crawl swimming, the snorkel use has the limitation of not permitting the accomplishment of the tumble turn, making an open turn technique necessary. This will probably

increase the duration of the turning time during pool swimming and could affect the energetics of swimming. However, although empirical evidences have demonstrated that using a snorkel has an effect on turning times (Bentley et al., 2005; Komar et al., 2012; Seifert et al., 2010), no study has yet quantified it.

Recently a new version of the AquaTrainer® snorkel was developed for VO_2 measurements. The transformed snorkel is lighter and easier-to-use, enabling oxygen uptake measurements in more ecological swimming conditions, particularly when connected to the K4b² oximeter (Baldari et al., 2013). This respiratory apparatus was verified for gas analysis (Baldari et al., 2013; Gayda et al., 2010), but no measurements were made to evaluate if its specific design influences on hydrodynamic drag in a large range of velocities. Therefore, we have aimed to test the respiratory AquaTrainer® snorkel for hydrodynamic drag during front crawl swimming. We hypothesized that swimming attached to this snorkel will not lead to additional drag independently of exercise intensity. Complementarily, the effect of wearing the AquaTrainer® snorkel on turn times will be quantified to analyse the eventual “ecological disturbance” associated with its use. As it is not possible to perform the turning technique (the one traditionally selected during competition and in training conditions), we hypothesized that an evident increase in turning time will occur.

Material and Methods

Participants

Twelve national-level swimmers (mean \pm SD: age: 22.2 ± 6.3 years, height: 1.75 ± 0.05 m, body mass: 67.7 ± 5.7 kg, training background: 7.6 ± 5.4 years and training frequency: ≥ 7 units per week, percentage of the 100 m world record: $83.16 \pm 16.42\%$) were tested. All swimmers had previous experience in swimming with the AquaTrainer® respiratory snorkel and with the testing procedures, as they were involved in previous VO_2 evaluations. Participants provided informed written consent (or parent/guardian when swimmers were

under 18 years) in all the procedures of data collection, which was approved by the local ethics committee and in accordance with the IJSM standards (Harriss and Atkinson, 2013).

Experimental design

Subjects were tested in a 25 m indoor pool (1.90 m deep), with a water temperature of 27.5 °C, on two consecutive days (24 h apart). In the first session, subjects were randomly assigned to perform on the measuring active drag system (MAD-system, (Toussaint et al., 1988), two repetitions (without and with snorkel, 1 h rest) of a slow to maximal velocity test consisting of 12 x 25 m (3 min passive rest). On the second day, swimmers randomly performed three turns (20 min passive rest): a tumble turn without snorkel and two open turns (one with snorkel and other without it) during a 15 m in 15 m out bout with a progressive increase in swimming velocity (ensuring that the 5 m in and 5 m out section was performed at maximal intensity). Both experimental sessions were preceded by a 20 min warm-up of low to moderate swimming intensity, involving of 10 min free-swimming and 10 min performing on MAD-system.

AquaTrainer® snorkel

The new AquaTrainer® snorkel was specifically designed to reduce hydrodynamic drag and increase the users' comfort comparing to the older version (Fernandes et al., 2013), with the following structural upgrades (Baldari et al., 2013): (i) in-line arrangement of more flexible, but not stretchable, 35 mm calibre inspiratory and expiratory tubes (0.86 m length); (ii) a system to balance both tubes in a underwater stable position; (iii) a smaller, lighter and comfortable mouthpiece (oval rubber); and (iv) a softer, flexible and anatomically oriented head connection support.

Data analysis

Hydrodynamic active drag was measured using the MAD-system, which required swimmers to directly push-off fixed pads (with a standard distance of 1.35 m in-between) attached to a 23 m rod fixed at 0.8 m below water surface.

The rod was instrumented with a force transducer, allowing measurement of momentary push-off force at each pad, and the calculation of the mean force along one lane (16 pads in total; Ribeiro et al., 2013). Following Toussaint et al. (1987), swimmers used their upper limbs only with the lower limbs elevated and constrained with a pull buoy.

The force signal was acquired by an A/D converter (BIOPAC Systems, Inc.) at a sample rate of 1000 Hz and filtered with a low pass digital filter with a cut-off frequency of 10 Hz (Ribeiro et al., 2013). Assuming that each swimmer performed at a constant mean swimming velocity, the mean force equals the mean drag force, with the 12 velocity/drag ratio data being least square fitted according to Equation 1:

$$D = A.v^n \quad (1)$$

where D is total active drag, v is swimming velocity and A and n are parameters of the power function. For each participant, A and n were estimated using equation (1) (Matlab version R2012a, Mathworks, Inc) with a Levenberg-Marquardt algorithm (Toussaint et al., 1988; Toussaint et al., 2004). An individual example, as well as pool sample drag-velocity curves, without and with the use of the respiratory snorkel, are presented in Figure 1. Afterwards, active drag values were estimated (by interpolation) for 0.9, 1.1, 1.3, 1.5 and 1.7 m.s⁻¹ swimming velocities, for both experimental conditions.

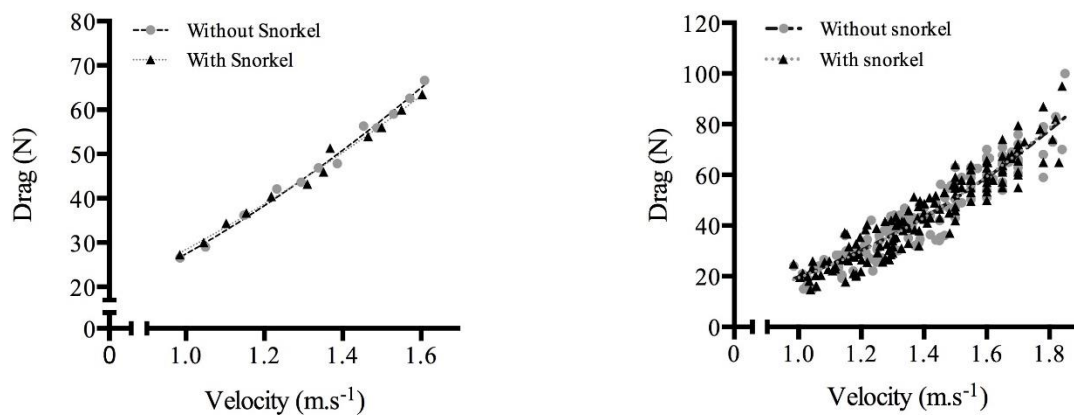


Figure 1. Typical individual example (left panel) and poll sample (right panel) active drag-velocity curves when swimming without and with the AquaTrainer® snorkel.

To compare open and tumble turns performance participants were videotaped with a camera (Sony® DCR- HC42E, 1/250 digital shutter, Nagoya, Japan) operating at 50 Hz placed 0.30 m below the water surface on a waterproof box (Sony® SPK-HCB, Tokyo, Japan) at the lateral wall of the pool and at 6.78 m from the plane of movement and in line with 5 m reference. The analyzed turn section was defined by 5 m in and 5 m out and turning time was expressed by time difference between the swimmers' head passing the underwater 5 m mark (vertical edge of a rigid calibration structure) before and after the swimmers contact the turning wall.

Statistical analysis

Mean and standard deviation (SD) values were used for descriptive analysis of all studied variables and measures of skewness, kurtosis and Shapiro-Wilk test allowed to assess data normality and homogeneity. The sphericity was checked by the Mauchley test. Differences in active drag, A and n between conditions (without and with snorkel) were tested using paired-sample t -tests (IBM® SPSS Statistics).

Agreement between active drag values without vs with snorkel conditions was evaluated using: (i) Passing-Bablok regression (MedCalc Software, v. 11.6, Mariakerke, Belgium) quantifying the mean of the differences (bias) between

the two experimental conditions (one of them used as the reference) and calculating the regression parameters (slope and intercept) to observe if there was proportional or fixed bias between conditions, as indicated by their confidence intervals of 95% (95% CI). A 95% CI that includes the 1 for the slope and the 0 for the intercept allow rejecting the hypothesis of proportional and fixed differences, respectively (Passing and Bablok, 1983); (ii) Bland-Altman analysis (STATA 13.0 software, StataCorp, Inc.) that graphically represented the difference in scores between pairs of measurements (without and with snorkel) and the mean \pm 1.96 SD of the differences. This calculation provides an interval (95% CI) within which 95% of differences between measurements of the two conditions were expected to lie (Bland and Altman, 1986); and (iii) Pitman's test (STATA 13.0 software, StataCorp, Inc.) of difference in variance calculating the correlation between difference (without and with snorkel) and mean drag values (Pitman, 1939). A one-way repeated measures ANOVA, with Bonferroni post-hoc test (IBM® SPSS Statistics) was used to compare the three turning conditions.

Results

The mean \pm SD values of the hydrodynamic active drag for both without and with snorkel swimming conditions, obtained at different velocities, are given in Table 1. Data revealed that active drag increased with swimming velocity both when swimming without and with snorkel and equivalent drag values were observed between conditions for all the studied range of velocities. Complementarily, similar A and n mean \pm SD values were obtained when swimming unimpeded and with snorkel, respectively: 20.35 ± 5.05 vs 20.75 ± 4.50 ($p = 0.231$; [95% CI: -0.30 – 1,11]) and 2.40 ± 0.44 vs 2.35 ± 0.39 ($p = 0.352$; [95% CI: -0.16 – 0.06]).

Table 1. Mean \pm SD active drag values during both swimming without and with the AquaTrainer® snorkel conditions. The p value and 95% confidence interval (95% CI) are also presented.

Conditions	Swimming velocities				
	0.9 m.s ⁻¹	1.1 m.s ⁻¹	1.3 m.s ⁻¹	1.5 m.s ⁻¹	1.7 m.s ⁻¹
Drag without snorkel (N)	15.84 \pm 5.32	25.60 \pm 6.69	38.37 \pm 8.04	54.64 \pm 10.06	74.77 \pm 14.09
Drag with snorkel (N)	16.18 \pm 4.81	26.03 \pm 6.17	38.88 \pm 7.56	55.08 \pm 9.55	74.92 \pm 13.14
p	0.235	0.316	0.517	0.757	0.952
95% CI	[-0.26 – 0.94]	[-0.47 – 1.32]	[-1.15 – 2.15]	[-2.58 – 3.45]	[-4.94 – 5.22]

For all the studied velocities, the Passing-Bablok regression analysis reported slope and intercept values that include the 1 and the 0 (no deviation from linearity), respectively (Figure 2, left panel), and the Bland-Altman plots revealed a consistent distribution with all the values inside the limits of agreement (Figure 2, right panel). The results of Pitman's test confirmed that there is no association between the difference of the two tested conditions and their mean values of drag, for all velocities ($p \geq 0.05$).

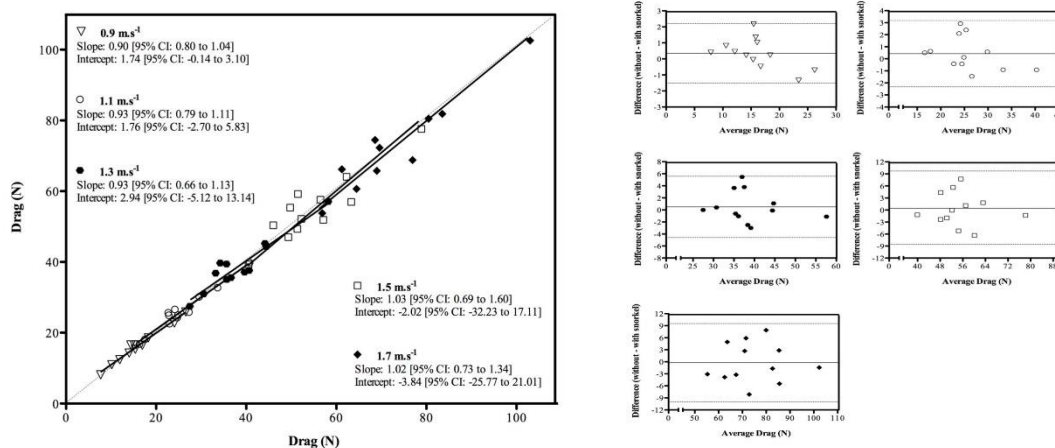


Figure 2. Passing-Bablok analysis (left panel, the solid and dashed lines indicate the regression equations and the identity, respectively) and Bland-Altman plots (right panel, the solid and dashed lines indicate mean difference and 95% confidence interval, respectively) of the differences in active drag obtained swimming without and with the AquaTrainer® snorkel for each studied velocity.

The mean \pm SD values of turning time were 5.83 ± 0.24 , 5.00 ± 0.28 and 5.53 ± 0.22 s for the open turn performed with snorkel, tumble turn and open

turn without snorkel (respectively). The open turn performed with snorkel was 0.83 ± 0.27 (14.2%, $p < 0.01$; [95% CI: 0.60 to 1.07]) and 0.30 ± 0.21 s (5.1%, $p < 0.01$; [95% CI: 0.15 to 0.45]) slower than the tumble turn and open turn without snorkel, respectively. The latter was 0.53 ± 0.22 (10.4%, $p < 0.01$; [95% CI: 0.35 to 0.71]) slower than the tumble turn.

Discussion

The aim of this study was to observe if the use of the new Cosmed AquaTrainer® snorkel lead to an increase of the hydrodynamic active drag of front crawl swimming. Furthermore, turning time was quantified to analyse the eventual “ecological disturbance” of using a respiratory snorkel during swimmers’ physiological testing and advice. Although being recently proposed, the new AquaTrainer® snorkel was already used for ventilatory data assessment in swimming (eg. de Jesus et al., 2014; Sousa et al., 2014b) but, despite classified as an easy-to-care equipment (with little mechanical constraints), no hydrodynamic characterization was conducted so far.

In the current study, hydrodynamic drag was assessed using the MAD-system that allows measuring active drag in a large range of swimming velocities (Toussaint et al., 2004). Using this approach the swimmer’s technique might present some alterations since the push off is made from fixed pads rather than from moving water. However, considering that this circumstance seems to not influence the determination of drag (Schreven et al., 2013) and since other methodologies have important limitations on its assessment - they are indirect evaluations (Di Prampero et al., 1974), restricted to maximal velocities (Kolmogorov and Duplishcheva, 1992) and limited to a stable position during gliding from the wall (Mollendorf et al., 2004) - we have favoured the MAD-system procedure. As expected, results were in line with the literature (Dal Monte et al., 1994; Toussaint et al., 1987; Toussaint et al., 2004), showing an approximately quadratic increase in active drag with swimming velocity, for both

unimpeded and with snorkel conditions. In fact, values in-between 1.69 and 2.82 were observed before (Hollander et al., 1985; Toussaint et al., 2004), in line with the range found in the current study [1.64 – 2.85]. This non-linear increase in active drag might be explained by the increasing importance of pressure and wave components of drag at higher velocities (Toussaint et al., 1988).

Our main finding was the absence of additional hydrodynamic drag when swimming front crawl attached to the AquaTrainer® snorkel. This is in agreement with Toussaint et al. (1987) that, also using the MAD-system (velocities ranging from 0.8 to 1.9 m.s⁻¹), found no drag effect when swimming with a snorkel with low caliber tubes (30mm). Also, Dal Monte et al. (1994) found no additional drag when comparing the passive drag (measured in a swimming flume, at velocities ranging from 1.1 to 2.1 m.s⁻¹) of a human shape dummy without and with a special streamlined snorkel (an immersed elliptical tube integrating both the expiratory and inspiratory ones). These authors even claimed that the snorkel condition could reduce the dummy total drag by improving the hydrodynamics of the leading edge.

In line with the above referred studies and contrarily to those that suggested a snorkel drag effect (Barbosa et al., 2010; Kjendlie et al., 2003), the hypothesis that AquaTrainer® snorkel condition does not lead to additional drag during swimming was confirmed, complementing its validation regarding on ventilatory data measurements (Baldari et al., 2013). Hence, it is now shown that this swimming specific snorkel device does not affect the energy cost of front crawl swimming even if any disturbance of swimmers' technique could be demonstrated in the future. In fact, future research should include the analysis of snorkel effect in eventual kinematical changes, by comparing alternated (front crawl and backstroke) and simultaneous (breaststroke and butterfly) swimming techniques, once contradictory and limited data have been presented (Barbosa et al., 2010; Conceição et al., 2013; Kjendlie et al., 2003).

Regarding the second aim of the current study, the additional turning time observed in the snorkel condition vs. the conventional tumble was lower than the values previously presented in empirical studies (between 1.17 and 1.60 s; Bentley et al., 2005; Komar et al., 2012; Seifert et al., 2010), which may indicate that the new AquaTrainer® ergonomic design facilitates performing the open turn technique. It should be taken into account that, in the current study, the open turn itself was ~10% slower than tumble turn, leading to the assumption that only the remaining ~4% delay might be attributed to a “snorkel use effect”. In fact, a ~5% difference was observed when the open turn with snorkel was compared to the unimpeded open turn condition. A similar time difference (4.75%) between two 100 m (50-m length swimming pool) front crawl bouts, performing the open turn unimpeded vs AquaTrainer® (first version) snorkel conditions, was reported previously (Barbosa et al., 2010). These differences might be attributed to an additional drag during the 180° turning movement of the head as, throughout this phase, the “lateral side” of the snorkel is exposed to water-flow.

In addition, due to the short length tubes of the snorkel, the open turn needs to be performed near the water surface and, so, higher drag values could be experienced due to the importance of wave drag component. In fact it was observed before that water depth has a positive effect on reducing the wave drag during gliding of the wall (Lyttle et al., 1998; Vennell et al., 2006). To gain maximum passive wave drag reduction benefits, swimmers should glide at ~0.6 m underwater (Lyttle et al., 1998), but this condition is hard to accomplish when using the respiratory snorkel. These constraints should be considered on swimmers testing sessions and respiratory snorkel future upgrades should contemplate this drawback.

In summary, the new version of the respiratory AquaTrainer® snorkel does not increase active hydrodynamic drag during front crawl swimming, not negatively influencing the specific exertion of the swimmer and, consequently, swimming energetics. Nevertheless, as an unusual (and slower) turning technique is

required, the restrictions associated to the snorkel use leads to an additional time that should be addressed in data analysis both for research and training and advice situations.

Chapter 4

Metabolic and ventilatory thresholds assessment in front crawl swimming.

João Ribeiro¹, Pedro Figueiredo^{1,2}, Mónica Sousa¹, Kelly de Jesus¹, Kari Keskinen³, João P. Vilas-Boas^{1,4}, Ricardo J. Fernandes^{1,4}.

¹ Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal

² Higher Education Institute of Maia, Maia, Portugal

³ Finnish Society of Sport Sciences, Helsinki, Finland

⁴ Porto Biomechanics Laboratory, University of Porto, Porto, Portugal

Published on Journal of Sports Medicine and Physical Fitness (2015), 55 (7-8), 701-707.

Abstract

The purpose of this study was to assess and characterise the ventilatory anaerobic threshold in swimming, and to verify if the anaerobic metabolic threshold could be accurately estimated using ventilatory parameters. Twenty-eight national-level male swimmers performed a n x 200 m front crawl individualized intermittent incremental protocol, with 30 s rest intervals, until exhaustion. The ventilatory variables and heart rate were continuously measured using a telemetric portable gas analyser. The capillary blood samples for lactate concentration analysis were collected from the earlobe at rest, during rest intervals, and at the end of exercise. No significant differences were observed between the ventilatory and metabolic thresholds for lactate concentration, heart rate and velocity ($p=0.62$, 0.80 and 0.78 , respectively). The Bland-Altman plot revealed higher agreement between both methods for heart rate and velocity values. Ventilatory anaerobic threshold occurred at a swimming velocity corresponding to 88% of maximal oxygen uptake and lactate concentration mean values at ventilatory and metabolic thresholds were lower than 3 mmol.l^{-1} . Swimming anaerobic metabolic threshold could be accurately estimated using ventilatory parameters. Moreover, ventilatory anaerobic threshold occurred at similar $\% \dot{V}O_{2\max}$ than in other sports. The lactate concentration mean values at ventilatory and metabolic thresholds were lower than the reference value of 4 mmol.l^{-1} evidencing that, in highly trained swimmers, individualized values of anaerobic threshold should be used instead of general references.

Key words: Bioenergetics, aerobic exercise, anaerobic threshold, ventilation, lactate

Introduction

From a complex group of sports performance determining factors, aerobic capacity is of major importance (Gastin, 2001). This capacity has been commonly described by the anaerobic threshold (AnT), a concept that dates back to the 1960s, and refers to the highest sustainable exercise intensity at which the balance between production and removal of blood lactate remains constant (Faude et al., 2009; Fernandes et al., 2011).

Although the AnT concept is widely recognized and has commonly been applied for training prescription, there is no consensus on its theoretical basis and, consequently, there is ongoing debate on the topic and its controversies (for reviews see Faude et al., 2009, Hopker et al., 2011 and Svedahl and MacIntosh, 2003). While there is no single marker for AnT, there are a wide variety of diagnostic strategies for exercise testing procedures and mathematical treatment of data. These methodologies are commonly described by standardized references either to (i) a metabolic change in blood lactate concentrations ($[La^-]$), being the AnT commonly determined based on the point of the $[La^-]$ vs velocity relationship where an exponential rise in $[La^-]$ occurs – the metabolic anaerobic threshold (AnT_{Met}), and (ii) ventilatory gas exchange data, when the exercise intensity associated with AnT is exceeded due to a nonlinear increase in ventilation – the ventilatory anaerobic threshold (AnT_{Vent}).

Some studies conducted in runners, cyclists and team sport athletes have shown that AnT_{Met} was strongly related to AnT_{Vent} (Anderson and Rhodes, 1991; Edwards and Macfadyen, 2003; Wasserman et al., 1973). However, there are considerable uncertainties about this assumption, as the AnT_{Met} and AnT_{Vent} could be coincident for a given workload but not necessarily physiologically dependent on each other (Edwards and Macfadyen, 2003).

In the particular case of swimming, agreement between methods has never been tested and the AnT assessment has used methodologies mainly based on

[La⁻] values rather than ventilatory parameters. To date, there has been minimal investigation using AnT_{Vent} in swimming (Smith et al., 1984; Roels et al., 2005) probably due to the difficulty of implementing oxygen uptake ($\dot{V}O_2$) measurements in swimming pool conditions. Moreover, swimming is performed in horizontal position in water which may influence the physiological responses compared to the other land based activities such as cycling and running (Aspenes and Karlsen, 2012; Pluto et al., 1988; Stenberg et al., 1967). It has been suggested that exercising while in a horizontal position induces a lower sympathetic stimulation, $\dot{V}O_2$ and heart rate (HR) values, while earlier [La⁻] accumulation could also occur (Pluto et al., 1988; Holmer, 1974). Moreover, swimming is conducted in an aquatic environment, which leads to some metabolic and circulatory changes, and requires an elevated respiratory work due to the higher external pressure (Holmer, 1974; Heinicke et al., 2001), which could in turn explain the higher-respiratory capacity of swimmers (Aspenes and Karlsen, 2012). In addition, swimming presents with lower propulsive efficiency, in comparison to land sports, due to higher hydrodynamic resistance (the density of the water is about 800 times that of the air), requiring a large energy expenditure (Di Prampero, 1986). Understanding these physiological and biomechanical characteristics, together with the lack of information on AnT_{Vent} in swimming, it was the aim of this study to assess and characterize the AnT_{Vent}, and to determine if swimming AnT_{Met} could be accurately estimated using ventilatory parameters.

Material and Methods

Participants

Twenty-eight national-level male swimmers between ages of 15 and 24 years and 3.08 years of training background and percentage of the 200 m world record 89.96 ± 16.71 % volunteered to participate in the study. All swimmers were assessed for height, weight, and percentage body fat. Body mass index was calculated as weight divided by height square, and fat mass were assessed

through the bioelectric impedance analysis method (Tanita TBF 305, Tokyo, Japan).

Participants were asked to abstain from smoking and consuming alcohol or caffeine in the 48 h prior to exercise testing, and to avoid strenuous exercise 12 h prior to exercise testing. They were also previously familiarized with the test procedures and equipment used in the experiment. All of the participants (or parent/guardian when subjects were under 18 years) provided informed written consent before data collection, which was approved by the Ethics Committee of Faculty of Sport from the University of Porto. The procedures were performed according to the Declaration of Helsinki.

Experimental procedure

The test session took place in a 25 m indoor pool, 1.90 m deep, with a water temperature of 27.5 °C, and air humidity of 55%. Each swimmer performed an individual warm-up, which consisted of low to moderate intensity 1200 m aerobic swimming. Following the warm-up, the subjects performed a $n \times 200$ m ($n \leq 8$) front crawl individualized intermittent incremental protocol, with 30 s rest intervals (cf. Fernandes et al., 2008). The last step velocity was set at the best performance in the 400 m front crawl event that the swimmers were able to accomplish at the time of the experiments; then successive $0.05 \text{ m}\cdot\text{s}^{-1}$ were subtracted from the swimming velocity corresponding to the referred hypothetical time, allowing the determination of the mean target velocity for each step. During the protocol, the swimming velocity was controlled through a visual pacer (TAR. 1.1, GBK-electronics, Aveiro, Portugal), with flashing lights on the bottom of the pool to help swimmers to keep the predetermined swimming velocity. Participants were encouraged to give a maximal effort in the last step of the protocol. In-water starts and open turns, always performed to the same lateral wall side, were used. Capillary blood samples for $[\text{La}^-]$ analysis were collected from the earlobe at rest, during the 30 s rest intervals, at the end of exercise, and in recovery periods at 1, 3 and 5 min, and were analysed using a portable lactate analyser (Lactate Pro, Arkay, Inc., Kyoto, Japan). The $\dot{V}\text{O}_2$,

carbon dioxide (CO_2), minute ventilation (V_E) and HR were directly and continuously measured using a telemetric portable gas analyser (K4b², Cosmed, Rome, Italy), connected to a special respiratory snorkel (Aquatrainer, Cosmed, Rome, Italy). This device allowed swimmers to exercise without restriction, and breath-by-breath measurements were obtained (cf. Baldari et al., 2012). The device calibration was performed before each test according to manufacturer's specifications.

Data analysis

The individual breath-by-breath $\dot{V}\text{O}_2$ responses were smoothed using a 3-breath moving average and time-average to produce a standard weighted response at 5 s intervals as proposed previously (Sousa et al., 2011). The $\dot{V}\text{O}_{2\text{max}}$ was considered to be reached according to primary and, at least, three secondary traditional physiological criteria: (i) occurrence of a plateau in $\dot{V}\text{O}_{2\text{max}}$ despite an increase in swimming velocity, and (ii) high levels of $[\text{La}^-]$ ($\geq 8 \text{ mmol.l}^{-1}$), elevated respiratory exchange ratio ($R \geq 1.0$), elevated HR ($> 90\%$ of $[220 - \text{age}]$), and (iii) exhaustive perceived exertion (controlled visually and case-by-case). The mean of the last minute of each step was used to assess the V_E value for each step velocity (Fernandes et al., 2003).

The AnT_{Met} and AnT_{Vent} were mathematically assessed through $[\text{La}^-]/\text{velocity}$ and $V_E/\text{velocity}$ curves modelling, using the least square method (cf. Fernandes et al., 2011): both AnT_{Met} and AnT_{Vent} were assumed to be the interception point of a combined pair of regressions (linear and exponential) used to determine the exact point for the beginning of an exponential rise (Figure 1). In addition, AnT_{Met} and AnT_{Vent} were confirmed using visual inspection by two independent experienced researchers. The AnT_{Vent} was also checked through a different methodology, i.e., by determining the visual inspection of an overproportional increase on V_E as related to CO_2 output, (cf. Meyer et al., 2005).

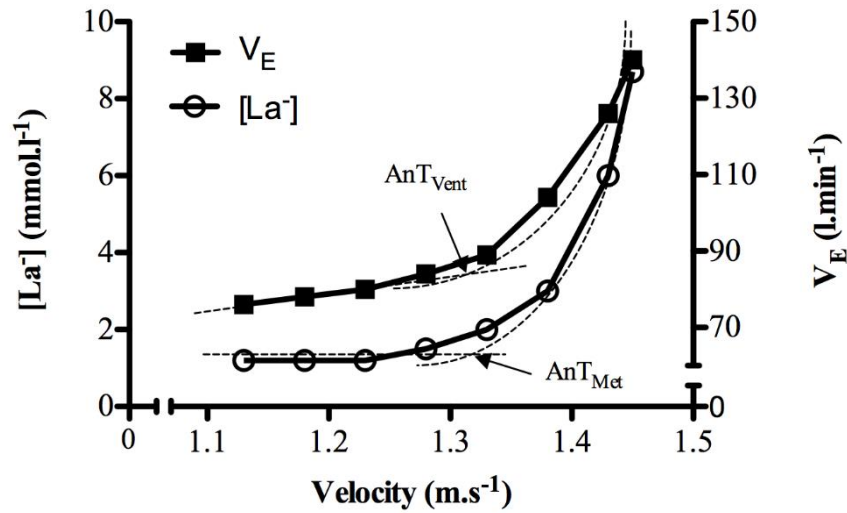


Figure 1. Example of blood lactate concentration ($[La^-]$) and pulmonary ventilation (V_E) to velocity curves for metabolic and ventilatory anaerobic thresholds assessment. The interception of a linear and exponential lines are represented.

The HR and $\dot{V}O_2$ corresponding to the velocity of AnT_{Met} and AnT_{Vent} were assessed by linear interpolation or extrapolation of the HR and $\dot{V}O_2$ to velocity curves, respectively; AnT_{Vent} was also expressed as percentage of $\dot{V}O_{2max}$.

Data analysis

The normality of distribution was checked using the Kolmogorov-Smirnov test. Descriptive statistics (mean, range and standard deviation) from all measured variables were calculated. Agreement between methods was made comparing mean data of HR and velocity at AnT_{Met} and AnT_{Vent} , and the Bland-Altman plots. The Bland-Altman analysis included the plot of the mean value of velocity at AnT_{Met}/HR at AnT_{Met} and velocity at AnT_{Vent}/HR at AnT_{Vent} vs the delta value (i.e., difference) between velocity at AnT_{Met}/HR at AnT_{Met} and velocity at AnT_{Vent}/HR at AnT_{Vent} . It was adopted as limits of agreement a bias of ± 1.96 standard deviation of the difference. In addition, a Bland-Altman trend option plot was also considered for velocity at AnT_{Met} and AnT_{Vent} . This analysis considered a linear relationship between the paired difference ($v@AnT_{Met} - v@AnT_{Vent}$) and the paired average. Comparison between means of $[La^-]$, HR

and velocity at AnT_{Met} and AnT_{Vent} was made using paired-samples *t*-tests. These statistical analyses were performed using STATA 10.1 (StataCorp, USA) and the level of significance was set at 5%.

Results

Table 1 presents the characteristics of study participants and the metabolic and ventilatory variables values assessed in the intermittent incremental swimming protocol.

Table 1. Anthropometric characteristics of male swimmers (n=28) and metabolic and ventilatory parameters assessed during the intermittent incremental swimming protocol.

Parameters	Mean \pm SD	Range
Age (yrs)	19.33 \pm 2.90	15 - 24
Height (m)	1.79 \pm 0.08	1.69 - 1.89
Weight (kg)	73.56 \pm 4.93	66 - 83
Body Mass Index (kg.m ⁻²)	22.98 \pm 2.75	19 - 26
Estimated fat (%)	9.14 \pm 2.95	6 - 14
[La ⁻]@ AnT_{Met} (mmol.l ⁻¹)	2.58 \pm 0.67	1.23 - 3.93
[La ⁻]@ AnT_{Vent} (mmol.l ⁻¹)	2.60 \pm 0.78	1.22 - 4.30
V_E @ AnT_{Vent} (l.min ⁻¹)	88.56 \pm 14.69	62.34 - 126.01
% VO_{2max} @ AnT_{Vent} (ml.min.kg ⁻¹)	87.99 \pm 6.27	70.47 - 97.41
HR@ AnT_{Met} (b.min ⁻¹)	164.0 \pm 8.5	141.0 - 176.0
HR@ AnT_{Vent} (b.min ⁻¹)	163.7 \pm 10.9	137.0 - 178.0
v@ AnT_{Met} (m.s ⁻¹)	1.30 \pm 0.05	1.22 - 1.47
v@ AnT_{Vent} (m.s ⁻¹)	1.31 \pm 0.07	1.19 - 1.51

[La⁻]@ AnT_{Met} : blood lactate concentrations corresponding to the metabolic anaerobic threshold;
 [La⁻]@ AnT_{Vent} : blood lactate concentrations corresponding to ventilatory anaerobic threshold;
 V_E @ AnT_{Vent} : minute ventilation corresponding to the anaerobic ventilatory threshold;
 % VO_{2max} @ AnT_{Vent} : percentage of maximal oxygen uptake at ventilatory anaerobic threshold;
 HR@ AnT_{Met} : heart rate at metabolic anaerobic threshold; HR@ AnT_{Vent} : heart rate at ventilatory anaerobic threshold;
 v@ AnT_{Met} : velocity corresponding to metabolic anaerobic threshold;
 v@ AnT_{Vent} : velocity corresponding to ventilatory anaerobic threshold.

No significant differences were observed between AnT_{Met} and AnT_{Vent} for [La⁻], HR and velocity (p=0.62, 0.80 and 0.78, respectively). The Bland-Altman plot of the difference between velocity and HR at AnT_{Met} and AnT_{Vent} is reported in Figure 2 (A and B panels, respectively).

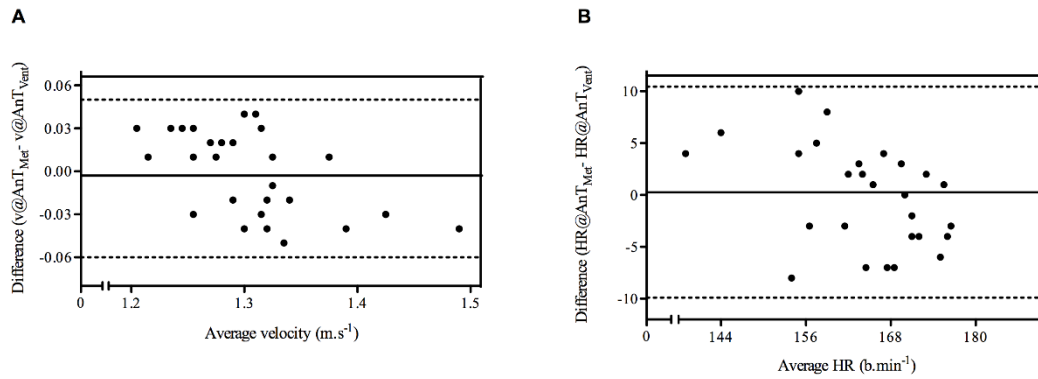


Figure 2. Comparison between the metabolic and ventilatory thresholds by Bland and Altman scatter of plots for velocity (left panel) and heart rate (right panel). Average difference line (solid lines) and 95% CI (dashed lines) are indicated.

Considering the velocity variable, the average difference was -0.003 (95% CI -0.015 to 0.009), with limits of agreement ranging from -0.059 to 0.055. Regarding the HR parameter, the average difference was 0.25 (95% CI -1.76 to 2.26), with limits of agreement ranging from -9.93 to 10.4. For both conditions, the Bland-Altman plots revealed a consistent distribution with all subjects between the limits (average \pm 1.96 SD) indicating a higher agreement. The Bland-Altman trend plot (Figure 3) revealed that the difference in velocity ($v@AnT_{Met} - v@AnT_{Vent}$) tended to become progressively more negative the higher the velocity values were.

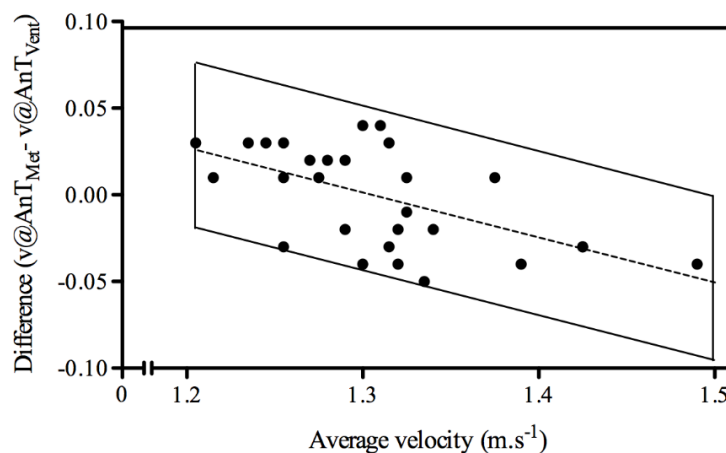


Figure 3. Bland-Altman trend plot considering the linear relationship between the paired difference ($v@AnT_{Met} - v@AnT_{Vent}$) and the average velocity. Average difference trend line (dashed line) is also represented.

Discussion

The purpose of the present study was to assess and characterize the AnT_{Vent} among swimmers (intermittent incremental front crawl swimming protocol) and comparing it with the AnT_{Met} . The main findings were that both ventilatory and metabolic $AnTs$ occurred at similar swimming velocities and HR values. Moreover AnT_{Vent} occurred at a swimming velocity corresponding to 88% of $\dot{V}O_{2max}$ and the $[La^-]$ mean values at AnT_{Vent} and AnT_{Met} were lower than 3 mmol.l⁻¹.

Taking into consideration the $[La^-]$, both metabolic and ventilatory $AnTs$ values obtained in this study were similar with those previously observed among well aerobically trained swimmers (Fernandes et al., 2008; Michele et al., 2012). Furthermore, these values occurred at a lower $[La^-]$ compared to the averaged 4 mmol.l⁻¹, a value proposed by Mader et al. (1978), and traditionally used for assessing metabolic AnT . Stegmann & Kinderman (1982), have also found that the $[La^-]$, corresponding to AnT for aerobically trained subjects, was lower than the traditionally accepted 4 mmol.l⁻¹ value. Additionally it has been noted that the use of 4 mmol.l⁻¹ seems not to take into account the individual kinetics of the $[La^-]$ curve, thereby ignoring the individual variability among subjects (Fernandes et al., 2011; Svedahl and MacIntosh, 2003). Consequently, the results of our study and those of the studies of others indicate that the use of the 4 mmol.l⁻¹ value as a mark of the AnT may limit the robust evaluation of individual aerobic capacity.

The AnT_{Vent} , occurred at a swimming velocity, corresponding to 88% of $\dot{V}O_{2max}$, which is in agreement with Roels et al. (2005) that also implemented a test protocol conducted in swimming pool conditions. Studies carried out in other sports reported similar AnT_{Vent} percentage of $\dot{V}O_{2max}$ (Bunc et al., 1987; McLelland and Cheung, 1992). Thus, although $\dot{V}O_{2max}$ is considered specific to each exercise modality and lower $\dot{V}O_{2max}$ has been attributed to swimming (Roels et al., 2005; Pluto et al., 1988; Holmer, 1974), this phenomenon seems

not to affect the $\% \dot{V}O_{2\max}$ at which the AnT_{Vent} occurs in swimming. In fact, AnT_{Vent} could be improved and/or altered without a change in $\dot{V}O_{2\max}$. Moreover, at submaximal swimming intensities some ventilatory variables associated with AnT_{Vent} (V_E , respiratory quotient and ventilatory coefficient) demonstrated similar responses to those reported in running (Holmer, 1974). Roels et al. (2005) also reported no significant AnT_{Vent} differences between swimming and cycling, performed in either groups of swimmers and triathletes.

Taking into consideration the main objective of the present study, there were no significant differences between AnT_{Met} and AnT_{Vent} for $[La^-]$, HR and velocity; and high agreement between methods was observed. These findings indicate that AnT_{Met} could be estimated using ventilatory parameters and corroborates the hypothesis of several studies conducted in other sports, which evidence that AnT_{Met} could be linked to the AnT_{Vent} (Anderson and Rhodes, 1991; Wasserman et al., 1973). This assumption has been established based on the occurrence of increased buffering when a net production of $[La^-]$ occurs. To minimize the magnitude of change in blood pH, several buffer systems are involved, including the bicarbonate system; the reaction of H^+ with bicarbonate results in the formation of carbonic acid, which dissociates to H_2O and CO_2 . This excess of CO_2 , concomitant with decrease in pH, seems to stimulate ventilation.

In the present study, some subjects had a tendency towards a slightly lower velocity at AnT_{Vent} than at the AnT_{Met} ; this suggests that the detected increase in ventilation should not be exclusively attributed to buffering of lactic acid. In fact, metabolic acidosis cannot be solely responsible for changes in V_E and the AnT_{Vent} occurrence (Busse et al., 1992), and there is no biochemical evidence that lactate production causes acidosis (Robergs et al., 2004). There are other physiological parameters that contribute to increased ventilation during exercise, namely CO_2/H^+ stimulation of the carotid bodies, respiratory mechanics, temperature effects, and skeletal muscle neurogenic stimulation (Svedahl and MacIntosh, 2003). Some studies performed with McArdle's disease patients (a metabolic disorder in which affected individuals do not

produce substantial amounts of La^-) have shown ventilatory breakpoints at higher exercise intensities during incremental tests despite not observable AnT_{Met} (Hagberg et al., 1982).

Finally, considering the negative tendency revealed in trend plot data, it may be concluded that the AnT_{Vent} tends to occur later than AnT_{Met} as the velocity increases. This might indicate that for aerobically well-trained swimmers (with higher velocity at AnT) the occurrence of AnT_{Vent} is related to the AnT_{Met} , and we believe that, for these cases, the overproportional increase in ventilation could be more influenced by metabolic parameters (Ward, 2000). On the other hand, for swimmers with lower velocity at AnT (e.g., sprinters or swimmers anaerobically well-trained), the AnT_{Vent} might occur earlier than AnT_{Met} , probably due to a variety of feedback and feed forward mechanisms (cf. Ward, 2000) responsible for increasing ventilation, and not necessarily due to metabolic acidosis. Nevertheless, this study did not quantify training volume/intensity or swimmers' training background, requiring further research to establish those assumptions. Hence, as study limitation it should be stated that the comparison between metabolic and ventilatory parameters did not consider the swimmers training specialty nor the preferred stroke technique.

Conclusions

This study showed that AnT_{Vent} could be successfully assessed using a swimming incremental intermittent protocol typically used to monitor swimmers' aerobic capacity. While AnT_{Vent} and AnT_{Met} were directly proportional to each other, the present study supports the hypothesis that swimming AnT_{Met} could be estimated using ventilatory parameters, once metabolic and ventilatory estimations were in agreement, and revealed to be valid for the determination of the AnT velocity in swimming. While the assessment of AnT_{Vent} is a non invasive technique, it presents some disadvantages, particularly the cost of portable gas analysers, the equipment constraints (the snorkel and valve systems), and the heavy and long lasting setups, which may be difficult to apply

and operate in training conditions. On the other hand, the portable lactate analysers allow more practical and convenient assessment of the AnT_{Met} , even though it is slightly invasive. In addition, since AnT_{Vent} in swimming occurred at similar $\% \dot{V}O_{2max}$ than in other sports, we suggest that the water environment and the exercise position did not have influence on the percentage velocity at which the $\dot{V}O_{2max}$ occurred.

Acknowledgments

This investigation was supported by grants of Portuguese Science and Technology Foundation (PTDC/DES/101224/2008) (SFRH/BD/81337/2011).

Chapter 5

Biophysical determinants of front crawl swimming at moderate and severe intensities.

João Ribeiro^{1,2}, Argyris Toubekis³, Pedro Figueiredo^{4,5}, Kelly de Jesus^{1,2}, Huub Toussaint⁶, Francisco Alves⁷, João P. Vilas-Boas^{1,2}, Ricardo J. Fernandes^{1,2}.

¹ Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal

² Porto Biomechanics Laboratory, University of Porto, Porto, Portugal

³ Department of Aquatic Sports, Faculty of Physical Education and Sports Science, Kapodistrian University of Athens, Athens, Greece

⁴ School of Physical Education, Federal University of Rio Grande do Sul

⁵ Department of Kinesiology, University of Maryland

⁶ Amsterdam University of Applied Sciences, School of Sports and Nutrition, Amsterdam, Netherlands

⁷ Faculty of Human Movement Technical University of Lisbon, Lisbon, Portugal

Submitted for publication on International Journal of Sports Physiology and Performance.

Abstract

Our purpose was to conduct a biophysical analysis of the factors associated with front crawl performance at moderate and severe swimming intensities, represented by the anaerobic threshold (v_{AnT}) and maximal oxygen uptake ($\dot{V}O_{2max}$) velocities. Ten high-level male swimmers performed two front crawl intermittent incremental tests of 7x200 m and 12x25 m (through a system of underwater push-off pads) to assess v_{AnT} and $\dot{V}O_{2max}$ and power output (respectively). The first protocol was videotaped (3D reconstruction) for kinematic analysis to assess stroke frequency, stroke length, propelling efficiency and index of coordination. Moreover, $\dot{V}O_2$ was directly measured and capillary blood samples for lactate concentrations were collected enabling to compute the metabolic power. The second protocol allowed calculating mechanical power and performance efficiency from the ratio between mechanical and metabolic power. Both v_{AnT} and $\dot{V}O_{2max}$ were not explained by stroke frequency, stroke length, propelling efficiency, index of coordination and metabolic power variability. $\dot{V}O_{2max}$ was explained by the power to overcome drag ($r=0.77$; $p\leq 0.05$) and performance efficiency ($r=0.72$; $p\leq 0.05$), in contrast with the non-association between these parameters and v_{AnT} ; both velocities were well related ($r=0.62$; $p\leq 0.05$). When considering high-level swimmers, the biomechanical parameters, coordination and metabolic power seemed not to be performance discriminative at both moderate and severe intensities. However, the increase in power to overcome drag, for the less metabolic input, should be the focus of any intervention that aims to improve performance at severe swimming intensity. This is also true for moderate swimming intensities, as v_{AnT} and $\dot{V}O_{2max}$ are proportional to each other.

Keywords: Kinematics, power, propelling efficiency, coordination, energy expenditure, front crawl.

Introduction

Swimming velocity is the product of stroke frequency (SF) and stroke length (SL) (Craig et al., 1985; Pendergast et al., 2006) and is coupled with the qualitative organization (coordination) of upper and lower limbs movements that determine propelling efficiency (η_p) (Chollet et al., 2000; Seifert et al., 2015). It is also determined by the useful power to overcome drag forces (P_D) for a given finite metabolic power (\dot{E}), whose interrelation origins the performance (or drag) efficiency (η_D) (Toussaint and Hollander, 1994; Zamparo et al., 2008). This overall idea indicates that the combination of biomechanical, energetic and coordinative factors plays a decisive role in swimming locomotion and that parameters representing each one of these areas should be frequently monitored to develop better training processes and, consequently, to excel performance.

In swimming training programs the moderate and severe intensity domains are considered critical once they represent the most trained bioenergetical areas: the capacity and power of aerobic system. The development of these training areas is usually done by assessing the velocity at anaerobic threshold (v_{AnT}) and the minimum velocity that elicits maximal oxygen uptake ($\dot{V}O_{2max}$) and, consequently, by developing specific training series to improve oxidative potential (Fernandes et al., 2008; Maglischo, 2003; Olbrecht, 2000). In fact, improvement of these training velocities will shift critical intensity domains to a more favourable performance enhancement zone and could be the base for the velocity increment in the extreme intensity domain, where most of the competitive events take place.

Previous studies have already reported that some biomechanical, energetic and coordinative parameters show abrupt changes at/after the v_{AnT} (Figueiredo et al., 2014; Keskinen and Komi, 1993; Psycharakis et al., 2008), but this was not yet analysed for the $\dot{V}O_{2max}$. Moreover, although the main $\dot{V}O_{2max}$ influencing factors were already determined - energy cost, maximal lactate concentrations

([La⁻]) and the general stroking parameters; (Fernandes et al., 2006; Fernandes et al., 2008) - no studies verified which are the determinants of vAnT.

Hence, as swimming performance is biophysically based (Barbosa et al., 2010; Pendergast et al., 2006), and both aerobic capacity and power seem to be relevant for increasing performance in most of the competitive distances (Maglischo, 2003; Olbrecht, 2000; Toussaint and Hollander, 1994), the purpose of the current study was to conduct a biophysical analysis of the factors associated with front crawl performance at vAnT and $\dot{V}O_{2\max}$, representing the moderate and severe intensities.

Material and Methods

Participants

Ten high-level male swimmers (mean \pm SD: age: 19.78 \pm 4.31 years, height: 1.81 \pm 0.07 m, body mass: 71.40 \pm 5.72 kg, training background: 12.47 \pm 3.86 years and percentage of the 200 m world record: 81.63 \pm 2.71%) volunteered to participate in the current study. Swimmers were familiarized with the test procedures and the equipment used in the experiment (previously approved by the local ethics committee and performed according to the Declaration of Helsinki). Subjects avoided strenuous exercise and abstained from smoking and consuming alcohol or caffeine 48 h prior to exercise testing.

Experimental procedure

Each swimmer accomplished two testing sessions, separated by at least 2 h rest in a 25 m indoor pool (1.90 m deep) with a water temperature of 27.5 °C and 60% of air humidity. In the first session, subjects performed a 7 x 200 m front crawl intermittent incremental test, with increments of 0.05 m.s⁻¹ and 30 s resting intervals between steps, using in-water starts and open turns (Fernandes et al., 2011). Initial velocity was established according to the individual level of fitness and set at the swimmer's individual performance on the 400 m front crawl swimming minus seven increments of velocity. To help

maintaining the pre-defined individual velocities, a visual pacer with flashing lights (GBK-pacer, GBK-electronics, Aveiro, Portugal) was placed on the bottom of the swimming pool and the elapsed time was taken using a chronometer (Seiko, 140, Tokyo, Japan). In the second session, swimmers performed another intermittent incremental test, but this one consisted in 12 x 25 m front crawl, from slow to maximal velocity (with 3 min rest in-between), on the Measuring Active Drag System (MAD-system) (Ribeiro et al., 2013). This was done for obtaining data in the overall spectrum of swimming intensities.

Metabolic and energetic parameters

In the 7 x 200 test $\dot{V}O_2$ was directly measured using a telemetric portable gas analyser (K4b², Cosmed, Rome, Italy) connected to a specific respiratory snorkel and valve system (Aquatrainer, Cosmed, Rome, Italy), a breath-by-breath low hydrodynamic resistance device that allows swimming without relevant restrictions (Baldari et al., 2013; Ribeiro et al., 2015). Then, during data treatment, occasional $\dot{V}O_2$ breath values were omitted from the analysis by including only those in-between mean \pm 4 SD and the individual breath by breath $\dot{V}O_2$ responses were smoothed using a 3-breath moving average and time-averaged to produce a standard weighted response at 10 s intervals (Fernandes et al., 2012).

Capillary blood samples for $[La^-]$ analysis were collected from the earlobe at rest in the 30 s rest interval, at the end of exercise and during the recovery period (1, 3, 5 and 7 min after the end of the protocol) using a portable lactate analyser (Lactate Pro, Arkray, Inc., Kyoto, Japan). These data allowed assessing the AnT and corresponding vAnT through the $[La^-]$ vs. velocity curve modelling method, assumed to be the interception point of the best fit of a combined linear and exponential pair of regressions used to determine the exact point for the beginning of an exponential rise in $[La^-]$ (Fernandes et al., 2011).

$\dot{V}O_{2max}$ was considered to be reached according to primary and secondary traditional physiological criteria (Fernandes et al., 2008; Poole et al., 2008) with

all ventilatory parameters mean values being calculated using the last 60 s of exercise of each step enabling to directly detect $\dot{V}O_{2\max}$, or indirectly if a plateau less than 2.1 ml. kg⁻¹min⁻¹ could not be observed (Kuipers et al., 1985). \dot{E} was obtained through the addition of the net $\dot{V}O_2$ values and those resultant from the transformation of the net [La⁻] into O₂ equivalents, using the proportionality constant of 2.7 mlO₂ kg⁻¹ mM⁻¹ (di Prampero et al., 1978; Fernandes et al., 2006; Figueiredo et al., 2011).

Biomechanical parameters

The incremental 7 x 200 m test was recorded with a total of six stationary and synchronised video cameras (HDR CX160E, Sony Electronics Inc., USA), operating at a frequency of 50 Hz, with an electronic shutter velocity of 1/250 s. The space recorded was calibrated with a volume with dimensions (6.0 m x 2.5 m x 2.0 m, for x, z and y directions) with twenty-four points of calibration and the images synchronisation was obtained using a pair of lights observable in the field of view of each camera (De Jesus et al., 2015).

The video images were digitized using the Ariel Performance Analysis System (Ariel Dynamics, San Diego, USA) at a frequency of 50 Hz, considering twenty anatomical reference points (Zatsiorsky's model adapted by de Leva, 1996): vertex of the head and ear lobe, and right and left: acromion, lateral humeral epicondyle, ulnar styloid process, third distal phalanx, prominence of great femoral trochanter external surface, lateral femoral epicondyle, lateral malleolus, calcaneus, and hallux. A 3D reconstruction was accomplished using Direct Linear Transformation algorithm and a low pass digital filter of 5 Hz. The reliability of the digitizing process was calculated from two repeated digitisations of a randomly selected trial. The repeatability coefficient with the limits of agreement (95%), as described by Bland-Altman method, were described for horizontal centre of mass (CM) velocity 0.00941 m.s⁻¹ [-0.00821 to 0.0193]; and horizontal CM displacement 0.0017 m [-0.0026 to 0.0035].

Kinematic parameters were analysed through the mean value of two consecutive cycles in the mid-section of the swimming pool, captured in the penultimate lap of each step of the incremental test (i.e. at 175 m lap), defined as the period between two consecutive entries of the same hand. The body CM position as a function of time was computed and the mean velocity of swimming cycle was calculated by dividing the horizontal displacement of the CM over its total duration. The SF was determined from the time needed to complete one cycle and the SL by the horizontal displacement of CM.

Hand velocity was computed as the sum of the instantaneous 3D velocity of the right and left hands during the underwater phase and η_F was estimated from the ratio of CM velocity to 3D mean hand velocity. The computed efficiency represents the Froude/Theoretical efficiency (internal work is not considered) of the upper limb cycle only (cf. Zamparo et al., 2011) for a more detailed discussion).

Upper limbs coordination

Upper limbs coordination in the 7 x 200 test was obtained by determining the index of coordination (IdC), with each upper limb action being divided into four phases: entry, pull, push and recovery. The duration of each phase was measured for each upper limb cycle (with a precision of 0.02 s) and the duration of a complete cycle was the sum of all the four phases. The IdC represented the time gap between the propulsion of the two upper limbs as a percentage of the duration of the complete front crawl swimming cycle, shifting from catch-up ($\text{IdC} < 0\%$) to opposition ($\text{IdC} = 0\%$) and superposition ($\text{IdC} > 0\%$) modes (Chollet et al., 2000; Seifert et al., 2015).

All biomechanical, energetic and coordinative variables previous described herein were calculated for each one of the completed steps of the 7 x 200 m test. The best individual fitting was drawn for each variable vs. corresponding velocity allowing the v_{AnT} and $\dot{V}\text{O}_{2\text{max}}$ to be calculated by interpolation.

Power output

In the MAD-system condition during the 12 x 25 m test, swimmers pushed-off from fixed pads attached to a 23 m rod situated 0.8 m below water surface and with a standard distance of 1.35 m between each pad. The rod was instrumented with a force transducer, allowing measuring momentary push-off force at each pad and calculating the mean force along one lap (16 pads in total; Ribeiro et al., 2013). Swimmers used their upper limbs only with the lower limbs elevated and constrained with a pull buoy (Toussaint et al., 1987).

The force signal was acquired by an A/D converter (BIOPAC Systems, Inc.) at a sample rate of 1000 Hz and filtered with a low pass digital filter with a cut-off frequency of 10 Hz (Ribeiro et al., 2013). Assuming that each swimmer performed at a constant mean swimming velocity, his mean force equals the mean drag force, with the 12 velocity/drag ratio data being least square fitted according to equation (1):

$$D = A \cdot v^n \quad (1)$$

where D is total active drag, v is swimming velocity and A and n are parameters of the power function. For each subject, A and n were estimated using equation (1) (Matlab version R2012a, Mathworks, Inc) with a Levenberg-Marquardt algorithm (Toussaint et al., 1988; Toussaint et al., 2004). P_D was calculated, for both v_{AnT} and $\dot{V}O_{2max}$, as the product of the correspondent mean velocity and the mean force and η_D was assessed by the ratio between P_D and \dot{E} (Toussaint et al., 1990; Zamparo and Swaine, 2012).

Statistical analysis

Mean \pm SD computations for descriptive analysis were obtained for all variables and all data were checked for distribution normality with the Kolmogorov-Smirnov test. Comparison between means of the variables corresponding to each swimming intensity (v_{AnT} and $\dot{V}O_{2max}$) was made using paired samples *t*-test. Pearson's correlation coefficient was used to analyse the relationship

between the studied variables and respective moderate and severe intensities. Moreover, the coefficient of variation was applied at $vAnT$ and $\dot{v}VO_{2max}$ to detect extent of variability in relation to the mean performance. These statistical analyses were performed using SPSS 20.0 (IBM® Statistics) and the level of significance was set at 5%.

Results

Data concerning each swimmer individual biomechanical, energetic and coordinative values obtained at moderate and severe front crawl intensities, i.e. at $vAnT$ and $\dot{v}VO_{2max}$ (respectively) are presented in Figure 1.

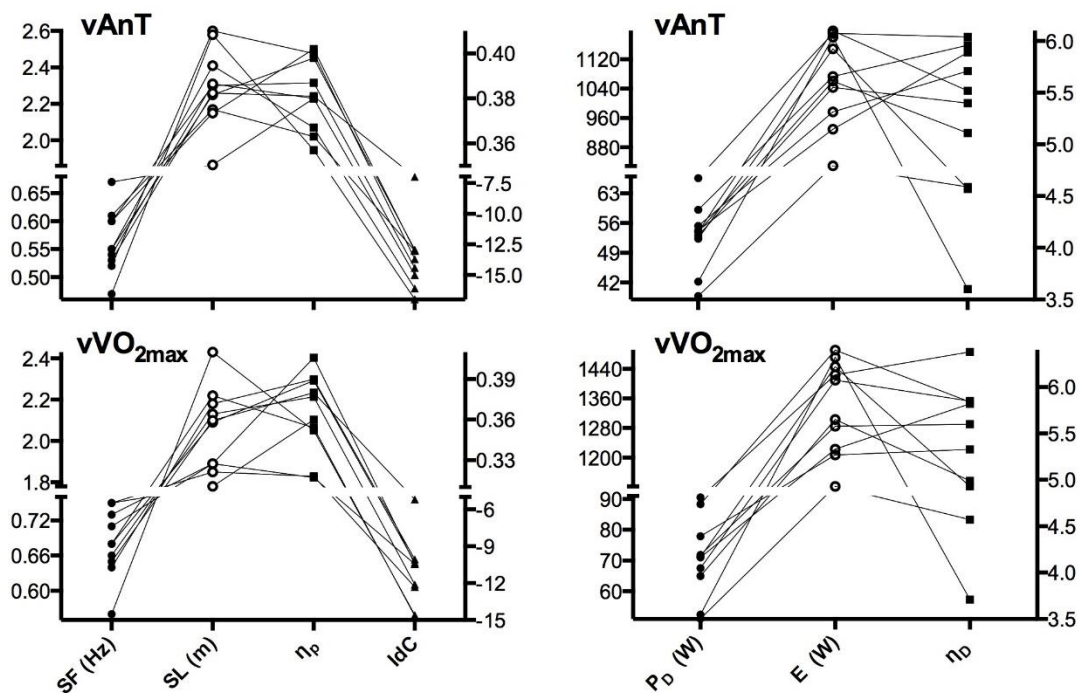


Figure 1. Stroke frequency (SF), stroke length (SL), propelling efficiency (η_p), index of coordination (IdC), power to overcome drag (P_D), metabolic power (\dot{E}) and performance efficiency (η_D) values obtained at both anaerobic threshold ($vAnT$, upper panel) and maximal oxygen uptake ($\dot{v}VO_{2max}$; lower panel) intensities for each studied swimmer.

It was perceived that swimmers used distinct intra-individual arrangements among the studied variables at moderate and severe intensities, but low performance variability was observed both for $vAnT$ (3.7 %) and $v\dot{V}O_{2max}$ (4.1%). The mean \pm SD values of SF, SL, P_D , η_P , IdC, $\dot{V}O_2$, $[La^-]$, \dot{E} , η_D at $vAnT$ and $v\dot{V}O_{2max}$ are reported in Table 1. Almost all parameters presented higher values at the most intense front crawl effort, with the major percentage increments observed in P_D , IdC and \dot{E} ($\dot{V}O_2$ plus $[La^-]$). Similar η_D values were found between swimming intensities, while SL and η_P were lower at $v\dot{V}O_{2max}$.

Table 1. Mean \pm SD values for stroke frequency (SF), stroke length (SL), propelling efficiency (η_P), power to overcome drag (P_D), index of coordination (IdC), oxygen uptake ($\dot{V}O_2$), lactate concentrations [La^-], metabolic power (\dot{E}) and performance efficiency (η_D) obtained at anaerobic threshold (AnT) and maximal oxygen uptake ($\dot{V}O_{2max}$) front crawl intensities, representing the moderate and severe swimming domains. Percentage and statistical significant differences (*; $p \leq 0.05$) between swimming intensities are also presented.

	v (m.s ⁻¹)	SF (Hz)	SL (m)	η_P	P_D (W)	IdC	$\dot{V}O_2$	[La^-]	\dot{E} (W)	η_D
AnT	1.35 \pm 0.05	0.56 \pm 0.06	2.29 \pm 0.21	0.38 \pm 0.02	52.97 \pm 7.81	-12.14 \pm 5.24	50.72 \pm 3.27	2.92 \pm 0.60	1063 \pm 122.90	5.24 \pm 0.78
$\dot{V}O_{2max}$	1.46 \pm 0.06*	0.68 \pm 0.06*	2.06 \pm 0.20*	0.36 \pm 0.03*	70.69 \pm 12.99*	-9.61 \pm 5.49*	59.88 \pm 4.07*	8.25 \pm 1.67*	1338.18 \pm 127.40*	5.30 \pm 0.78
Difference (%)	7.97 \pm 1.44	17.23 \pm 2.87	-10.10 \pm 4.89	-5.18 \pm 7.25	24.53 \pm 4.69	22.81 \pm 8.27	15.25 \pm 1.95	35.96 \pm 7.30	20.59 \pm 4.81	1.13 \pm 5.07

The relationships between v_{AnT} and $\dot{v}O_{2max}$ and the studied biomechanical, energetic and coordinative parameters at these intensities are represented in Table 2.

Table 2. Pearson correlation values between velocities at anaerobic threshold (v_{AnT}) and maximal oxygen uptake ($\dot{v}O_{2max}$) and stroke frequency (SF), stroke length (SL), propelling efficiency (η_P), power to overcome drag (P_D), index of coordination (IdC), metabolic power (\dot{E}) and performance efficiency (η_D) at moderate and severe intensities, respectively. Significant level values are shown by * ($p \leq 0.05$).

Variables	v_{AnT}	$\dot{v}O_{2max}$
SF	$r = 0.58$; $p = 0.08$	$r = 0.58$; $p = 0.08$
SL	$r = -0.29$; $p = 0.41$	$r = -0.49$; $p = 0.09$
η_P	$r = -0.39$; $p = 0.27$	$r = -0.26$; $p = 0.46$
P_D	$r = 0.60$; $p = 0.07$	$r = 0.77$; $p = 0.01^*$
IdC	$r = 0.28$; $p = 0.43$	$r = 0.16$; $p = 0.51$
\dot{E}	$r = 0.45$; $p = 0.20$	$r = 0.03$; $p = 0.90$
η_D	$r = 0.52$; $p = 0.12$	$r = 0.72$; $p = 0.02^*$
v_{AnT}	-	$r = 0.62$; $p < 0.01^*$

It was possible to observe a direct relationship between $\dot{v}O_{2max}$ and P_D and η_D . On the other hand, no association between these parameters and v_{AnT} was identified. Moreover, SR, SL, η_P and IdC were not associated to v_{AnT} and $\dot{v}O_{2max}$, while both velocities were directly related to each other.

Discussion

In the current study, biomechanical, energetic and coordinative factors were measured to identify their influence at the moderate and severe swimming intensities, represented by their mostly used indicators, the v_{AnT} and $\dot{v}O_{2max}$ (respectively). No statistical relevant association was found between the studied parameters and v_{AnT} , probably due to distinct individual performance determinants combinations and low inter-individual performance variability. However, despite most of the studied parameters were not related with $\dot{v}O_{2max}$, P_D and η_D were found to explain swimming performance at this

intensity. In addition, v_{AnT} and $\dot{V}O_{2max}$ were associated indicating the interdependence of these prominent aerobic endurance parameters.

v_{AnT} and $\dot{V}O_{2max}$ assessment in the current study was conducted in ecological swimming pool conditions using the 7 x 200 m intermittent incremental test that has been noticed to be a valid protocol for obtaining aerobically related metabolic and ventilatory data (Fernandes et al., 2011; Pyne et al., 2001). Moreover, taking into consideration that swimming mechanical power output is difficult to assess in ecological swimming conditions, it was assumed that P_D evaluated on the MAD-system was similar to the one expected in front crawl free-swimming (Toussaint et al., 2004).

The biomechanical variables SL, SL and η_p at v_{AnT} and $\dot{V}O_{2max}$ intensities are comparable with data reported in the literature (Fernandes et al., 2011; Figueiredo et al., 2013; Zamparo, 2006). As expected, superior SF, and lower η_p and SL, were observed at $\dot{V}O_{2max}$, compared with v_{AnT} since it is commonly assumed that higher velocities implying superior SF, necessarily compromise η_p and, consequently, SL (Figueiredo et al., 2013; Psycharakis et al., 2008; Zamparo et al., 2005). Nevertheless, when analysing these parameters for each velocity separately, they were not associated neither with v_{AnT} nor $\dot{V}O_{2max}$, likely due to the swimmers low inter-individual performance variability. This could also be justified by the fact that swimmers seemed to present distinct individual SF, SL and η_p combinations, while attaining a similar v_{AnT} or $\dot{V}O_{2max}$, not evidencing a particular profile that could partially explain the variability of these velocities.

The current upper-limb coordination values are in accordance with literature, evidencing an IdC increase from moderate to severe intensity exertion, indicating that swimmers are sufficiently flexible and adaptable to modify the coordination pattern according to velocity related constraints (Glazier et al., 2006; Seifert et al., 2007). This IdC adaptability seems to be more evident at SF lower than 0.75 Hz (as observed in the current study), a value below which

swimmers have several motor solutions (Potdevin et al., 2006; Seifert et al., 2007). Closely related to the above-mentioned findings, considering that SF and SL are control parameters of a specific coordination mode (Chollet et al., 2000 and Seifert et al., 2004), the absence of association between IdC and vAnT and $\dot{V}O_{2max}$ suggests that it might be a poor predictor of changes at the selected intensities. In fact, it were reported no IdC differences when comparing swimmers of similar performance level at velocities lower than 1.5 m.s^{-1} (Seifert et al., 2007). This indicates that at intensities analysed in the current study, minor inter-velocity discrepancies among swimmers were not enough to substantially alter drag (which depends on velocity square) and, consequently, modify IdC (Seifert et al., 2015).

The power values reported by us are in accordance with previous findings that described a mean power value of 89.2 W in tethered swimming at maximal lactate steady state (Pessôa Filho et al., 2014) and 82.4 W between AnT and $\dot{V}O_{2max}$ (Kolmogorov et al., 2010). Moreover, the same power % difference (~24%) between ventilatory threshold and peak oxygen consumption (115.4 ± 18.4 vs 149.6 ± 17.1 W) was previously revealed, but the absolute power values were superior in both conditions, compared to our results (Swaine, 1994). However, it should be taken into account, this experiment involved simulated swimming that provides the total power, whereas our values referred to P_D only. This P_D increase from AnT to $\dot{V}O_{2max}$ could be explained by its dramatically intensification with velocity, usually represented by a cube power association (Kolmogorov and Duplishcheva, 1992; Toussaint and Beek, 1992).

In the current study, P_D did not statistically explain vAnT as, at this specific intensity, the capability of the upper limbs to generate maximum mechanical power might be relatively less important than the ability to sustain a high level of aerobic capacity and economy. This consideration is in accordance with previous findings that revealed a gradual increase in the correlation magnitude of power and intensity with the decreasing distance, i.e. increasing velocity. In

fact, we have observed a strong relationship between P_D and $\dot{V}O_{2\max}$ corroborating previous findings (most of them in non-ecological conditions) for short, middle and long swimming distances - $0.56 < r < 0.93$ - (Hawley et al., 1992; Pessôa Filho et al., 2014; Sharp et al., 1982; Tomikawa and Nomura, 2009; Toussaint and Vervoorn, 1990).

As swimming at a specific velocity requires energy from both aerobic and anaerobic systems, not accounting both sources might result in an underestimation of \dot{E} , with impact on the performance physiological understanding. The \dot{E} values obtained in the current study, assessed taking into account both regimens, are in line with those previously reported for similar intensities (Fernandes et al., 2006; Fernandes et al., 2008), with the moderate intensity requiring lower \dot{E} values than the severe exertion. This could be explained by intensification of the \dot{E} values with the rise of swimming velocity (usually reported as non-linear relationship), justifying why a ~8% velocity increase led to a substantial increment of \dot{E} (~21%).

However, when analysing each velocity independently, the non-association between \dot{E} and both $vAnT$ and $\dot{V}O_{2\max}$ is not in line with the above-mentioned assumption. This could indicate that \dot{E} per se is neither a discriminative of performance variability at these specific intensities, nor a limiting factor in power production that should be, in turn, more dependent on the quantity and quality of propelling muscles (Toussaint and Beek, 1992). This could also be justified by the above-referred subjects' homogeneity, indicating that the small discrepancies in swimming velocity were not enough to explain \dot{E} variability.

The η_D values presented by our swimmers revealed that less than ~6% of \dot{E} can be transformed into P_D , corroborating previous findings where η_D was calculated based on active drag values (Pendergast et al., 1977; Toussaint et al., 1990; Zamparo et al., 2005). The η_D values similarity between $vAnT$ and $\dot{V}O_{2\max}$ seems to be justified by the typical pattern reported for gross efficiency

that is characterized by a curvilinear behaviour with increasing power (Kolmogorov et al., 2010). As at the 100% power corresponding to ventilatory threshold a plateau is reached (data obtained in cycle ergometer conditions; De Koning et al., 2012), this could indicate that our swimmers reached an almost constant η_D at v_{AnT} not evidencing differences comparing to $\dot{V}O_{2max}$.

The absence of association between η_D and v_{AnT} , counteracting with the relationship between η_D and $\dot{V}O_{2max}$, follows exactly the same association between P_D and these two swimming intensities, reflecting the dependence of η_D on power output (Toussaint et al., 1990). Hence, the relationship between η_D and $\dot{V}O_{2max}$ might express that swimmers who can reach higher P_D are more efficient in transforming the available \dot{E} to overcome drag, i.e., they are able to achieve larger P_D for an almost identical \dot{E} .

A possible explanation to the above-referred fact could be related to an eventual higher η_P , but, as previously reported, no relation was found between η_P and $\dot{V}O_{2max}$. It should be stated, though, that η_P estimation is limited to swimming/hand velocity ratio, not considering propulsion related components (drag, lift and vortex forces) (Gourgoulis et al., 2015; Triantafyllou and Triantafyllou, 1995), limiting the obtainment of a real measure of η_P . Other possible explanation is the η_D increase due to the rise in muscular efficiency, since the ability to generate muscle power is dependent on the movement frequency that determines active muscles velocity of contraction. Hence, if an association between SF and $\dot{V}O_{2max}$ exists (as observed for $p < 0.10$), muscular efficiency would be supposed to increase with velocity of contraction until an optimal value (1 Hz - 1.8 Hz, Ettema and Loras, 2009).

Finally, the relationship between v_{AnT} and $\dot{V}O_{2max}$ suggests that aerobic capacity is, at a certain point, a necessary component for success when performing at aerobic power intensity and vice-versa. This highlights the importance of developing both aerobic capacity and power processes,

consisting in two independent bioenergetical areas (although based on oxidative regimens), to achieve an optimum level of performance (Maglischo, 2003; Olbrecht, 2000).

Conclusions and practical applications

Despite the general stroking parameters, η_p , IdC and \dot{E} are considered relevant for front crawl locomotion, they were not performance discriminative at both moderate and severe intensities when considering a homogenous group of high-level swimmers. As higher power is required as swimming intensity rise, P_D and η_D were identified as $\dot{V}O_{2max}$ performance enhancers. Therefore, moderate and severe intensities should be frequently evaluated and the training process should focus on aiming to improve $\dot{V}O_{2max}$, and indirectly v_{AnT} , as both velocities seem to be proportional each other.

Acknowledgments

This investigation was supported by grants of Portuguese Science and Technology Foundation (PTDC/DES/101224/2008) (SFRH/BD/81337/2011).

Chapter 6

Effect of fatigue in spatiotemporal parameters during 100 m front-crawl event monitored through 3D dual-media automatic tracking.

João Ribeiro¹, Sara Tribuzi Morais², Pedro Figueiredo¹, K. de Jesus¹, João Paulo Vilas-Boas^{1,2}, Ricardo Jorge Fernandes^{1,2}.

¹ University of Porto, Faculty of Sport, CIFI2D, Porto, Portugal

² University of Porto, Porto Biomechanics Laboratory (LABIOME), Porto, Portugal

Published on XII International Symposium for Biomechanics and Medicine in Swimming (2014): 521-525.

Abstract

The purpose of the present study was to analyse the effect of fatigue on the three dimensional arm-stroke pattern during a 100 m front-crawl race. Six national level swimmers performed a 100 m front-crawl test at maximal intensity. The event was recorded with eight underwater and seven land cameras (Qualisys AB, Gothenburg, Sweden) using a full body retro-reflective marker setup. Swimming velocity, stroke frequency, stroke length, hand velocity, backward amplitude, amplitude slip, hand depth, width and range, and index of coordination were assessed for each 25 m lap. Differences between the four laps were analysed using a repeated measure ANOVA. Significant changes of analysed parameters were observed across the race, with exception of slip amplitude and hand depth, width and range. Thus, the analysis of spatiotemporal variables, under the influence of fatigue, should be understood as a relevant part of training monitoring aiming to increase performance, particularly when fatigue installs.

Key words: swimming, front crawl, dual-media kinematical tracking, fatigue

Introduction

Fatigue has been identified as a limiting factor in swimming with direct influence on performance. In short high-intensity swimming events performance could be compromised as a consequence of muscle force decrease, which characterise the specific fatigue of these events (Bonifazi et al., 1993 and Fitts, 1994). Specifically during 100 m front-crawl all-out effort it was reported a decrease in power production as a fatigue consequence, inducing changes on general stroking biomechanical parameters (Toussaint et al., 2006).

Propulsion in front crawl depends essentially on arm-stroke motion (Deschodt et al., 1999), being particularly linked to horizontal and vertical forearms and hands kinematics (Berger et al., 1995). Hence, understanding how fatigue affects stroke kinematics throughout short swimming events could be of considerable interest to optimize performance. Nevertheless, studies regarding the effect of fatigue on 3D arm-stroke kinematics, during these efforts, are still limited. Suito et al. (2008) found a significant reduction in hand velocity and peak angular velocity of shoulder adduction from the first to the second half of the 100 m event, in agreement with the study of Toussaint et al. (2006).

The purpose of the present study was to analyse the effect of fatigue on 3D arm-stroke kinematics during a 100 m front-crawl performed at maximal intensity.

Methods

Six trained male swimmers (mean \pm SD: age 25.47 ± 4.69 years, height 1.82 ± 0.04 m, body mass 73.14 ± 6.14 kg, years of training background 12.47 ± 5.43 , a training frequency higher than 7 training units per week and performance at the 100 m front crawl world record $86.34 \pm 3.41\%$) participated in the study. Testing took place in a 25 m indoor pool, 1.90 m deep, with a water

temperature of 27.5 °C. After a moderate intensity individual warm-up, subjects performed a 100 m front-crawl maximal effort, from a push off start and using open turns to eliminate the influence of the dive and gliding in the analysis of stroke cycle. The event was recorded using seven land and eight underwater cameras (Oqus 3+ and Oqus Underwater, Qualisys AB, Gothenburg, Sweden) operating at 60 Hz. The calibrated volume was defined using three calibrations – underwater, overwater and twin (to merge the first and the latter) – according to manufacturer's guidelines. Orthogonal axes were defined as x for the direction of swimming, y for the mediolateral direction and z for the vertical, where $z=0$ defines the water surface.

Data acquisition was performed with Qualisys Track Manager version 2.7 (Qualisys AB, Gothenburg, Sweden) and data post processing employed Visual3D (C-Motion, Germantown, MD, USA) using low pass digital filter of 6 Hz. Each swimmer was equipped with a full body retro-reflective marker setup. Acromion, lateral and medial humerus epicondyle, radius- and ulna-styloid processes, third distal phalanx, iliac crest, and anterior and posterior iliac spine, for both right and left sides, were the anatomical reference points selected. Figure 1 exhibits the marker setup and its different stages throughout the data acquisition and post processing procedure.

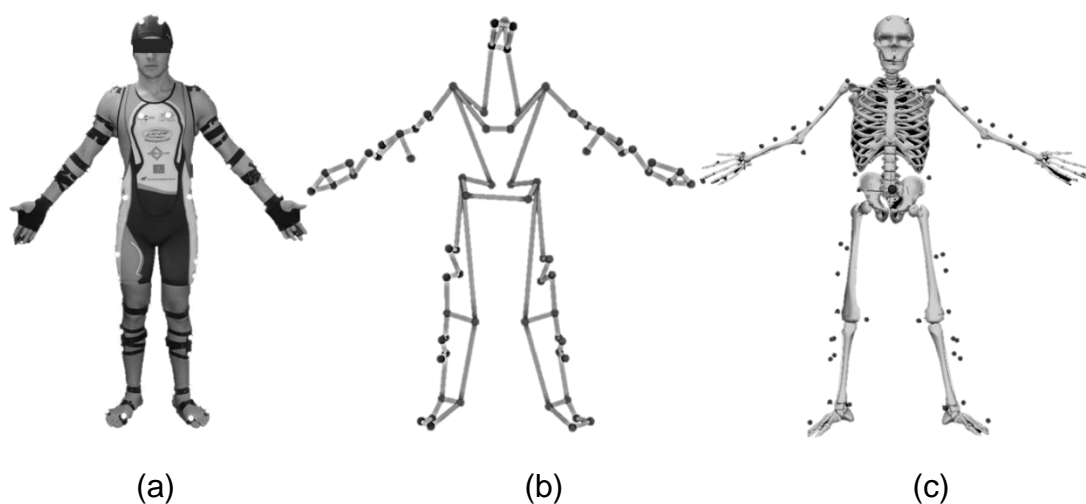


Figure 1. Full-body marker setup: (a) swimmer, (b) acquired in Qualisys Track Manager, and (c) post processed using Visual3D.

For the data analysis the front-crawl arm movements were split into four phases (adapted from Chollet et al., 2000), determined from the swimmer's x and z positions of the hand centre of mass (CM) and acromion: (i) entry and catch, between the first z negative coordinate and the beginning of the backward movement of the hand CM; (ii) pull, from the end of the entry and catch phase until the mid-underwater stroke position, determined by coincident x positions of hand CM and acromion; (iii) push, from the end of the pull until the hand release from the water, determined by the z positive coordinate of hand CM after the underwater trajectory; and (iv) recovery, from the end of the push until re-entry into the water of the hand CM.

For each 25 m lap, stroke frequency (SF) was assessed by the inverse of the time needed to complete one stroke cycle and the stroke length (SL) by the horizontal displacement of the pelvis CM. The mean velocity was computed by dividing the swimmer's average pelvis CM horizontal displacement by the time required to complete one stroke cycle.

The backward displacement and slip amplitudes were calculated through the difference between the coordinates of the most forward point and the most backward position of the hand CM, and of the entry and exit of the hand CM, respectively. The maximum hand depth was defined as the most negative vertical coordinate of the hand CM. The maximum hand width was defined as the maximum lateral coordinate of the hand CM with respect to the pelvis CM and the hand range calculated as the difference between the maximum and minimum lateral coordinates of hand CM at the pull phase with respect to the pelvis CM. Arm coordination was quantified using the index of coordination (IdC), which measures the lag time between the propulsive phases of the arms action, and was expressed as the percentage of the overall duration of the stroke cycle (cf. Chollet et al., 2000). Differences between the four laps were considered using a repeated measure ANOVA with LSD post-hoc test ($p \leq 0.05$).

Results

Mean±SD, p-value, and partial η^2 of ANOVA are displayed in Table 1 for general biomechanical parameters and, in Table 2, for the arm lengths and coordination.

Changes of analysed parameters were observed across the race as denoted by the significance level and high effect sizes.

Table 1. Mean±SD and statistical comparisons between the laps across the 100 m race for general biomechanical parameters.

Parameters	Lap 1	Lap 2	Lap 3	Lap 4	p	Partial η^2
Velocity (m.s ⁻¹)	1.53±0.07	1.45±0.08 ^a	1.33±0.05 ^{a,b}	1.33±0.07 ^{a,b}	< 0.001	0.83
Stroke frequency (Hz)	0.77±0.08	0.74±0.07	0.69±0.06	0.73±0.04 ^c	0.04	0.42
Stroke length (m)	1.98±0.16	1.97±0.22	1.96±0.13	1.83±0.16 ^{a,b,c}	0.01	0.51
Hand velocity (m.s ⁻¹)	2.40±0.22	2.30±0.25 ^a	2.12±0.18 ^{a,b}	2.07±0.14 ^{a,b}	< 0.001	0.84

^{a,b,c} Significantly different from the first, second and third lap, respectively. p<0.05.

Swimming velocity, SL, and hand velocity decreased along the 100 m. Contrarily, SF (last lap), backward amplitude and IdC (catch up coordination mode) increased.

No alterations of amplitude slip, hand depth, width and range were observed throughout the effort.

Table 2. Mean±SD and statistical comparisons between the laps across the 100 m race for general biomechanical parameters.

Parameters	Lap 1	Lap 2	Lap 3	Lap 4	p	Partial η^2
Backward amplitude (m)	0.53±0.06	0.55±0.05	0.53±0.04	0.56±0.04 ^{a,c}	0.005	0.56
Amplitude slip (m)	0.12±0.14	0.10±0.15	0.07±0.24	0.03±0.15	0.25	0.24
Hand depth (m)	-0.60±0.07	-0.60±0.06	-0.61±0.08	-0.60±0.07	0.59	0.11
Hand width (m)	0.38±0.13	0.35±0.11	0.39±0.11	0.37±0.08	0.22	0.25
Hand range (m)	0.31±0.09	0.30±0.09	0.33±0.08	0.33±0.08	0.06	0.37
Index of coordination	-10.28±2.22	-11.59±3.00	-10.15±4.20	-8.09±3.34 ^{a,b}	0.04	0.43

^{a,b,c} Significantly different from the first, second and third lap, respectively. p<0.05.

Discussion

The stroking parameters changed throughout the 100 m front crawl race as expected, in accordance with literature (Chollet et al., 1997, Vorontsov and Binevsky, 2003, Seifert et al., 2005 and Toussaint et al., 2006). Swimming velocity declined along the event as an effect of SL decrease (with statistical significance in the last lap), probably due to fatigue, which probably disabled swimmers to apply the same level of propulsive force, or to prevent drag, throughout the stroke towards the end of the race (Craig et al., 1985, Keskinen and Komi, 1993). SF showed a tendency to decrease until the third lap, but increased at the last 50m to compensate the decrease in SL, as an attempt to maintain velocity (Chollet et al., 1997 and Alberty et al., 2008). Concomitant with velocity decrease, hand velocity diminished along the effort, as previously observed (Suito et al., 2008 and Toussaint et al., 2006) likely due to the inability to maintain mechanical and muscular features (Aujouannet et al., 2006). This fact suggests that decreases in swimming velocity are probably caused by lower hand velocities, as it is considered to be one of the main propelling body segments in front-crawl technique (Suito et al., 2008).

Swimmers presented a catch up coordination mode during the 100 m race. In addition, as velocity and SL/SF ratio changed along the event, swimmers tended to adapt their IdC, in the final stages, by diminishing the lag time between propulsive phases, a fact that reveals the development of fatigue, as reported previously (Seifert et al., 2005, Alberty et al., 2005 and Alberty et al., 2008). Moreover, backward amplitude increased in the final lap suggesting that the forward point was likely increased once fatigued swimmers tended to augment the time during the entry phase, with the arm extended, before beginning the pull (Goldfuss and Nelson, 1971 and Aujouannet et al., 2006).

Values of hand depth, width and range were maintained stable throughout the effort, being similar to those presented previously for a 200 m maximal effort (Figueiredo et al., 2013). Therefore, even considering the impairments imposed

by fatigue, it is suggested that swimmers adapt their coordination, rather than stroke pattern, as a response to overcome fatigue.

Conclusion

The present findings showed that the swimmers' arm-stroke motion was altered by the induced fatigue. This fact could be useful for coaches and swimmers to understand the effects of fatigue on technical parameters of front crawl technique, as way to improve performance. Moreover, it showed that dual-media automatic tracking can be used successfully for Motion Capture of swimmers.

Acknowledgments

This investigation was supported by grants of Portuguese Science and Technology Foundation: PTDC/DES/101224/2008 (FCOMP-01-0124-FEDER-009577) and SFRH/BD/81337/2011.

Chapter 7

$\dot{V}O_2$ kinetics and metabolic contributions during full and upper body extreme swimming intensity

João Ribeiro¹, Pedro Figueiredo¹, Ana Sousa¹, Joaquim Monteiro^{1,2}, Jailton Pelarigo¹, João P. Vilas-Boas^{1,3}, Huub Toussaint⁴, Ricardo J. Fernandes^{1,3}

¹ Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal;

² REQUIMTE/FARMA, Faculty of Pharmacy, University of Porto, Porto, Portugal

³ Porto Biomechanics Laboratory, University of Porto, Porto, Portugal.

⁴ Amsterdam University of Applied Sciences, School of Sports and Nutrition, Amsterdam, Netherlands.

Published on European Journal of Applied Physiology (2015), 115, 1117-1124.

Abstract

Our purpose was to characterize the oxygen uptake ($\dot{V}O_2$) kinetics, assess the energy systems contributions and determine the energy cost when swimming front crawl at extreme intensity. Complementarily, we compared swimming full body with upper body only. Seventeen swimmers performed a 100 m maximal front crawl in two conditions: once swimming with full body and other using only the upper propulsive segments. The $\dot{V}O_2$ was continuously measured using a telemetric portable gas analyser (connected to a respiratory snorkel) and the capillary blood samples for lactate concentration analysis were collected. A sudden increase in $\dot{V}O_2$ in the beginning of exercise, which continuously rose until the end of the bout (time: 63.82 ± 3.38 s $\dot{V}O_{2peak}$: 56.07 ± 5.19 ml.min⁻¹.kg⁻¹; $\dot{V}O_2$ amplitude: 41.88 ± 4.74 ml.min⁻¹.kg⁻¹; time constant: 12.73 ± 3.09 s;) was observed. Aerobic, anaerobic lactic and alactic pathways were estimated and accounted for 43.4, 33.1 and 23.5% of energy contribution and 1.16 ± 0.10 kJ.m⁻¹ was the energy cost. Complementarily, the absence of lower limbs lead to a longer time to cover 100 m (71.96 ± 5.13 s), slower $\dot{V}O_2$ kinetics, lower aerobic and anaerobic (lactic and alactic) energy production and lower energy cost. Despite the short duration of the event, the aerobic energy contribution covers about 50% of total metabolic energy liberation, highlighting that both aerobic and anaerobic energy processes should be developed to improve the 100 m swimming performance. Lower limbs action provided an important contribution in the energy availability in working muscles being advised its full use in this short duration and very high intensity event.

Key words: Bioenergetics, oxygen uptake kinetics, energy contribution, energy cost, front crawl

Introduction

Competitive pool swimming events vary from short (50m, ~20 s) to long distances (1500, ~15 min), are performed at different intensities and place specific energetic demands on the metabolic system (Capelli et al., 1998; Figueiredo et al., 2011; Olbrecht 2000; Reis et al., 2010; Zamparo et al., 2000). In fact, performing a ~20 s effort involves the use of completely different metabolic pathways compared to those involved with longer swimming event lasting ~15 min (Olbrecht, 2000). Hence, the understanding of the metabolic profile of each swimming event of a swimmer is important, for designing appropriate training programs, to improve performance.

Studies that aimed at the determination of swimming energetics focused mainly on the assessment of oxygen consumption ($\dot{V}O_2$), but despite its response as a function of exercise intensity is well documented, researchers generally analysed it from low to severe swimming domains (de Jesus et al., 2014; Pessoa Filho et al., 2012; Reis et al., 2012a; Reis et al., 2013; Sousa et al., 2014). As the majority of the races are typically swum at faster paces (the duration of the 50, 100 and 200 m front crawl is within 2 min of exercise), measuring $\dot{V}O_2$ at lower intensities has limited application for a better understanding of the oxygen delivery to the working muscles as a performance limiting factor in swimming. In fact, research regarding $\dot{V}O_2$ kinetics assessment at extreme intensities compatible with race-like swimming conditions is scarce, existing only two studies that aimed to characterize the $\dot{V}O_2$ kinetics at 100 m (pilot study; Rodriguez et al. 2003) and 200 m (Sousa et al., 2011) front crawl.

Moreover, recently it has been suggested that, even for short duration swimming events, there is a relevant aerobic energy contribution that should be taken into consideration in the training process (Figueiredo et al., 2011; Peyrebrune et al., 2014). However, the available information regarding the relative contribution of each energy system to the overall energy supply of short duration but very intense swimming events is scarce. Assessing the total energy

expenditure and the energy cost of extreme swimming intensity events by considering aerobic, anaerobic lactic and alactic energy sources is an almost unexplored territory, with the exception of two studies conducted over 91.4 m (Capelli et al., 1998) and 200 m (Figueiredo et al., 2011) front crawl.

In addition, the $\dot{V}O_2$ kinetics, the energy expenditure and, consequently, the energy cost of swimming, depends on the amount of muscle mass involved in the exercise, particularly regarding lower limbs action contribution to the overall swimming propulsion. However, its importance in short and very intense swimming has been neglected since the lower limbs action is traditionally considered not very relevant due to the additional energy cost and the lack of evident benefits for propulsion (Toussaint et al., 1990a). In fact, no study has considered the effect of lower limbs action on $\dot{V}O_2$ kinetics, although few studies analyzed its influence on the aerobic and anaerobic contributions (but by performing in swimming flume conditions that is different from swimming freely in a pool; Ogita et al. 1996; Ogita et al. 2003). As it was recently suggested that a higher lower limbs action could present a positive effect on the overall propulsion, and that it could play an important role in coordination and wave drag and trunk inclination reduction during sprint front crawl swimming (Gourgoulis et al., 2014; Toussaint, 2011), the metabolic consequences of using an active action of the lower limbs on the overall swimmer's energetic profile should be analysed.

The purpose of this study was to characterize the $\dot{V}O_2$ kinetics, estimate the different energy systems contribution and calculate from that the energy cost of swimming at the extreme intensity domain. Complementarily, the referred physiological parameters were used to compare swimming full body with performing only with upper body, as it is suspected that the amount of active muscle mass, will influence the metabolic demand and, therefore, superior energy cost of exercise.

Methods

Seventeen well-trained male swimmers (mean \pm SD: 17.47 \pm 1.84 years of age, 1.80 \pm 0.06 m of height, 70.76 \pm 6.56 kg of body mass, 11.31 \pm 3.46 years of training background, \geq 7 units per week of training frequency) were tested. Their best performance in 100 m freestyle long course swimming was 56.26 \pm 2.42 s, corresponding to 117.94 \pm 11.71% of 100 m freestyle world male record. Participants volunteered to participate and provided informed written consent (or parent/guardian when subjects were under 18 years) before data collection. Swimmers avoided strenuous exercise and abstained from smoking and consuming alcohol or caffeine 48 h prior to exercise testing, and were previously familiarized with the procedures and experimental equipment (previously approved by the local ethics committee and performed according to the Declaration of Helsinki).

Experimental procedure

The test session took place in a 25 m indoor pool (1.90 m deep) with a water temperature of 27.5 °C and 60% of air humidity. Each swimmer accomplished two testing sessions, separated by at least 24 hours rest. Following a randomized order, in one session the subjects performed 100 m front crawl at maximum intensity swimming full body (S_{full}) and, in the other session, using only the upper body (S_{upper} , with the lower limbs supported by a standard pull-buoy). The buoyancy of the pull-buoy was 15.0 N when fully immersed and, since relative buoyancy for the lower limbs differed in-between subjects, it was checked if the swimmers' lower limbs were kept in a horizontal streamlined position during the entire bout. The two experimental conditions were preceded by an individual warm-up consisting on 15 min of low to moderate intensity. Ten min of passive rest were taken between warm-up and exercise bout to ensure that previous workout did not influence $\dot{V}O_2$ kinetics and exercise tolerance of the subsequent bout (Bailey et al., 2009). In-water starts and open turns (without gliding) were used in both S_{full} and S_{upper} .

$\dot{V}O_2$ was directly and continuously measured using a telemetric portable gas analyzer (K4b2, Cosmed, Rome, Italy) connected to a specific respiratory snorkel and valve system (Aquatrainer, Cosmed, Rome, Italy), which is a breath-by-breath low hydrodynamic resistance device (Baldari et al., 2013; Ribeiro et al., 2011) that allows swimming without restrictions. Previously to the experiment, the device reference air calibration was performed using a gas sample (16% oxygen and 5% carbon dioxide concentrations) and the flow meter was calibrated with a 3000 ml syringe.

Capillary blood samples for lactate concentration ($[La^-]$) analysis were collected from the earlobe at rest, at the end of exercise and in the recovery period (at 1, 3 and 5 min), and were analyzed using a portable lactate analyzer (Lactate Pro, Arkray, Inc., Kyoto, Japan). Prior to each test the device was calibrated according to manufacturer's specifications.

Data analysis

Firstly, the $\dot{V}O_2$ breath values were omitted from the analysis by including only those in-between mean \pm 4 SD. Afterwards, individual $\dot{V}O_2$ responses were smoothed using a 3-breath moving average and time-average to produce a standard weighted response at 5 s intervals (Sousa et al., 2011). For $\dot{V}O_2$ kinetics analysis, the data after the onset of exercise was fitted using the iterative Levenberg-Marquardt algorithm to a mono-exponential model where a nonlinear least squares method was implemented in MatLab environment for the adjustment of the function to $\dot{V}O_2$ data:

$$\dot{V}O_2 = \dot{V}O_{2b} + A \times (1 - e^{(-t/\tau)}) \quad (1)$$

where t (s) is the time, $\dot{V}O_{2b}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) is the basal oxygen uptake at the start of the exercise, A ($ml \cdot kg^{-1} \cdot min^{-1}$) is the $\dot{V}O_2$ amplitude and τ (s) stands for the time constant. The peak oxygen uptake ($\dot{V}O_{2peak}$) was obtained from the highest $\dot{V}O_2$ value recorded during the exercise.

Regarding the different energy systems contribution, the aerobic participation was calculated from the time integral of the net $\dot{V}O_2$ versus time relationship (Figueiredo et al., 2011; Sousa et al., 2014). The anaerobic contribution was estimated using a methodology (recognized to be valuable to have an approximation of the anaerobic energy demands during supra-maximal exercise in several forms of locomotion, as reviewed by Zamparo et al. (2011)) that considers the sum of the energy derived from lactic acid production with the one derived from phosphocreatine splitting in the contracting muscles. The lactic contribution (AnL) was calculated using the following equation (Figueiredo et al., 2011; Sousa et al., 2014):

$$AnL = \beta \times [La]_{net} \times M \quad (2)$$

where $[La]_{net}$ is the difference between the blood lactate accumulation after and before exercise, β is the energy equivalent for blood lactate accumulation ($2.7 \text{ ml } O_2 \cdot \text{mM}^{-1} \text{ kg}^{-1}$, di Prampero et al. (1978)) and M is the mass of the subject. The anaerobic alactic contribution ($AnAl$) was obtained considering (Capelli et al., 1998; Figueiredo et al., 2011; Sousa et al., 2013; Sousa et al., 2014; Zamparo et al., 2011):

$$AnAl = PCr(1 - e^{(-t/\tau)}) \times M \quad (3)$$

where t is the time duration, τ is the time constant of phosphocreatine splitting at work onset (23.4 s ; Binzoni et al. (1992)), M is the mass of the subject and PCr is the phosphocreatine concentration at rest assumed to be $18.5 \text{ m-mole} \cdot \text{kg}^{-1}$ (Capelli et al., 1998; Sousa et al., 2013; Sousa et al., 2014; Zamparo et al., 2011). The energy derived from the utilization of the phosphocreatine stores was estimated assuming that, in the transition from rest to exhaustion, its concentration decreases by $18.5 \text{ m-mole} \cdot \text{kg}^{-1}$ muscle (wet weight) in maximally active muscle mass (assumed to correspond to 30 and 20% of body mass in S_{full} and S_{upper} conditions, respectively). To express the energy expenditure in kJ

in the anaerobic alactic contribution, it was assumed a Phosphorus/Oxygen Ratio of 6.25 and an energy equivalent of $0.468 \text{ kJ.m-mole.kg}^{-1}$ (Capelli et al., 1998), while for the aerobic and anaerobic lactic energy contributions the energy equivalent was $20.9 \text{ kJ.lO}_2^{-1}$ (Figueiredo et al., 2011; Sousa et al., 2014; Zamparo et al., 2011). Based on these overall data, energy expenditure was assessed and energy cost was obtained as the ratio between energy expenditure and distance. The energy cost based on mechanical requirements was also estimated for comparison. Hence, assuming mechanical efficiency as 10%, propelling efficiency as 70% and drag as $30 \cdot \text{velocity}^2$ the estimated energy per meter $[(1/\text{mechanical efficiency}) \cdot (1/\text{propelling efficiency}) \cdot (\text{drag} \cdot 1 \text{ m})]$ was obtained (Toussaint, 2011; Toussaint et al., 1988; Toussaint et al., 1990b).

Statistical analysis

The normality of the data distribution was checked using the Kolmogorov-Smirnov test and descriptive statistics (mean \pm SD) from all measured variables were calculated. A paired sample t test was used to compare differences between S_{full} and S_{upper} conditions (level of significance was set at 5%).

Results

An individual example of the $\dot{V}\text{O}_2$ uptake kinetics during maximal S_{full} and S_{upper} bouts is presented in Figure 1. At the beginning of the swim, the S_{full} condition revealed an instantaneous and sudden $\dot{V}\text{O}_2$ increase, while a more moderate rise was observed in S_{upper} . In both circumstances $\dot{V}\text{O}_2$ continued to augment until the end of the bout (that ended later when swimming using only the upper body).

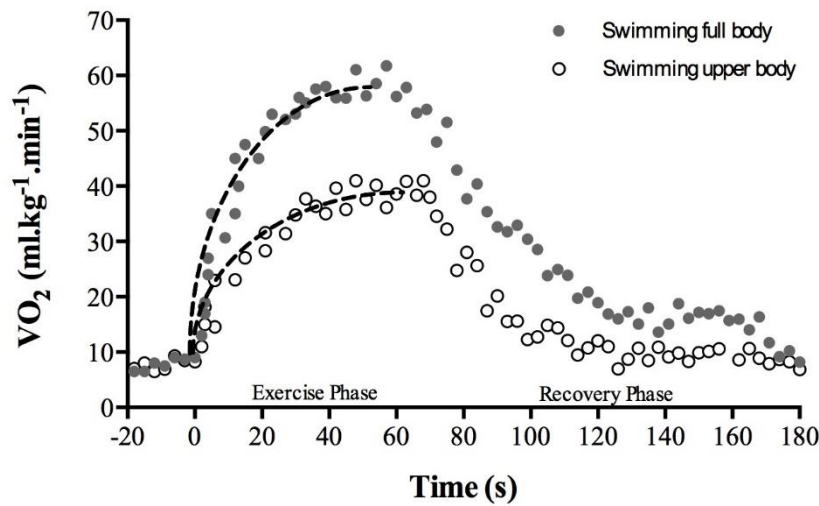


Figure 1. Typical example of a swimmer's oxygen uptake ($\dot{V}O_2$) kinetics during a extreme intensity swimming bout (100 m front crawl) using full body and upper body only.

Mean \pm SD values of time duration, speed, $\dot{V}O_{2peak}$, A, τ and $[La^-]$ during the maximal bouts are given in Table 1. When swimming full body, swimmers performed faster ($13.70 \pm 4.31\%$), developed a faster $\dot{V}O_2$ kinetics (as indicated by the lower τ values) and attained higher $\dot{V}O_{2peak}$, A and $[La^-]$ values ($p < 0.001$).

Table 1. Mean \pm SD of time duration, speed, peak oxygen uptake ($\dot{V}O_{2peak}$), oxygen uptake amplitude (A) and time constant (τ), as well as maximal lactate concentrations ($[La^-]_{max}$), after the maximal 100 m front crawl bouts performing with full body (S_{full}) and upper body only (S_{upper}).

	Time (s)	Speed (m.s ⁻¹)	$\dot{V}O_{2peak}$ (ml.kg ⁻¹ .min ⁻¹)	$\dot{V}O_{2peak}$ (l.min ⁻¹)	A (ml.kg ⁻¹ .min ⁻¹)	A (l.min ⁻¹)	τ (s)	$[La^-]_{max}$ (mmol.l ⁻¹)
S_{full}	63.82 \pm 3.38	1.58 \pm 0.07	56.07 \pm 5.19	3.97 \pm 0.49	41.88 \pm 4.74	2.96 \pm 0.39	12.73 \pm 3.09	11.25 \pm 1.60
S_{upper}	71.96 \pm 5.13*	1.39 \pm 0.09*	45.16 \pm 5.73*	3.21 \pm 0.59	34.21 \pm 6.99*	2.43 \pm 0.61	17.36 \pm 5.33*	8.01 \pm 1.79*

* Different from the S_{full} condition

To control the effect of different O_2 demands and time duration between S_{full} and S_{upper} conditions, $\dot{V}O_2$ responses were normalized to the difference between $\dot{V}O_{2b}$ and $\dot{V}O_{2peak}$, and time was expressed as percentage of bout duration, respectively, of each condition tested. The normalised $\dot{V}O_2$ response during maximal S_{full} and S_{upper} is presented in Figure 2 for a representative subject.

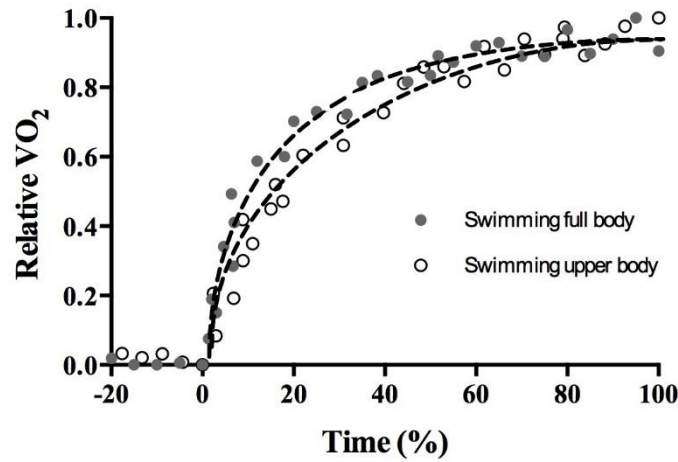


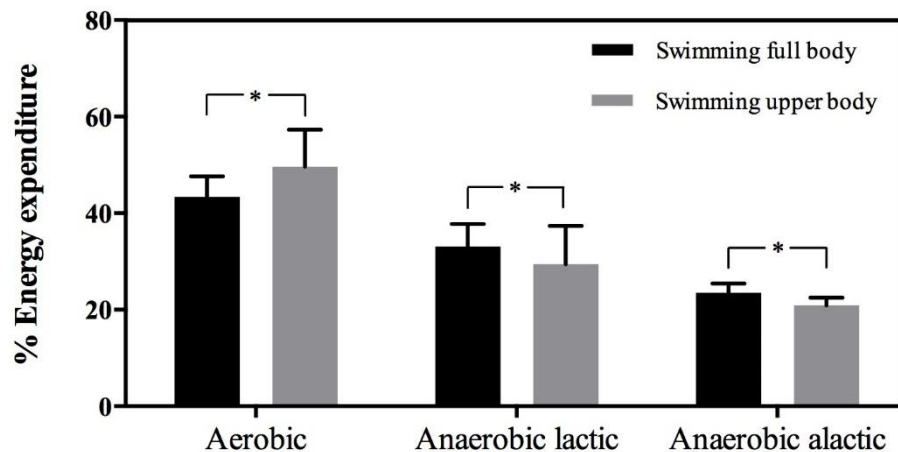
Figure 2. Typical example of a swimmer's oxygen uptake ($\dot{V}O_2$) kinetics normalized to $\dot{V}O_{2peak}$ and time percentage during extreme intensity swimming bout (100 m front crawl) using full body and upper body only.

As observed for the absolute values, the relative τ value in S_{full} was lower than S_{upper} condition: $28.88 \pm 8.86\%$ vs $36.22 \pm 13.54\%$ ($p=0.03$), respectively.

During this short duration and very high intensity swim, the energy resulting from aerobic, anaerobic lactic and alactic pathways when swimming full body were higher than those founded when performing only with the upper body: 49.31 ± 3.91 vs 45.12 ± 9.51 ($p = 0.04$), 39.01 ± 7.90 vs 26.98 ± 8.70 ($p < 0.001$) and 27.19 ± 2.51 vs 18.87 ± 1.72 kJ ($p < 0.001$), respectively.

The estimation for energy liberation for the different metabolic sources to the total energy expenditure during the 100 m front crawl maximal bouts are reported in Figure 3, being observed that aerobic pathway had the highest percentage contribution (followed by anaerobic lactic and alactic systems) for both S_{full} and S_{upper} conditions. Compared to S_{full} condition, swimming only with the upper body presented higher aerobic ($p = 0.001$) and lower anaerobic lactic ($p = 0.03$) and alactic ($p = 0.001$) percentage contributions.

Moreover, the energy cost was higher in S_{full} ($1.16 \pm 0.10 \text{ kJ.m}^{-1}$) in comparison to S_{upper} ($0.91 \pm 0.12 \text{ kJ.m}^{-1}$, $p < 0.001$). When these values were compared to the energy cost values estimated by mechanical requirements, no differences were observed between them for both S_{full} ($1.23 \pm 0.13 \text{ kJ.m}^{-1}$, $p = 0.12$) and S_{upper} ($0.98 \pm 0.15 \text{ kJ.m}^{-1}$, $p = 0.10$).



* Different from the swimming full body condition

Figure 3. Total energy expenditure derived from aerobic, anaerobic lactic and alactic energy sources in the maximal 100 m front crawl conditions.

Discussion

The purpose of this study was to characterize the $\dot{V}O_2$ kinetics, estimate the energy system contributions and assess the energy cost of locomotion in one of the most attractive swimming events - the 100 m freestyle (usually performed in front crawl) - that well represents performance at the extreme intensity domain. Complementarily, the influence of the use (or absence) of the lower limbs action was analysed. Our main findings could be summarized as follows: (i) a fast increase of the $\dot{V}O_2$ occurred at the beginning of the swim and continued to rise during the exercise, implying a high $\dot{V}O_2$ demand; (ii) an equal contribution of aerobic and anaerobic pathways to total energy liberation was found (if the participations of both lactic and alactic pathways are considered); (iii) the

energy cost values were high ($> 1.0 \text{ kJ}\cdot\text{m}^{-1}$). Complementarily, the absence of lower limbs action lead to a slower $\dot{V}\text{O}_2$ kinetics, induced lower aerobic and anaerobic (lactic and alactic) energy demand and revealed an inferior energy cost.

Regarding the $\dot{V}\text{O}_2$ kinetics, an instantaneous and sudden increase in $\dot{V}\text{O}_2$ from the beginning of the swim was observed that, continued to rise along the exercise. In fact, during extreme exercise intensity $\dot{V}\text{O}_2$ is not plateauing and continues to increase until the point of fatigue, precluding the $\dot{V}\text{O}_{2\text{max}}$ attainment (Burnley and Jones, 2007). Moreover, the observed $\dot{V}\text{O}_{2\text{peak}}$ values were similar to those obtained for the 100 m front crawl (Reis et al., 2010; Rodriguez et al., 2003), but lower than those presented for the 200 m front crawl (Sousa et al., 2011), evidencing that appropriate oxygen supply and utilization should not be neglected even in short duration swimming efforts (if conducted at maximal intensity). Corroborating these findings, the $\dot{V}\text{O}_2$ mean amplitude value was comparable to that previously described for extreme intensity effort (Sousa et al., 2011), but also similar to the values observed for severe intensity swimming (Fernandes and Vilas-Boas, 2012; Reis et al., 2012b; Sousa et al., 2014) where $\dot{V}\text{O}_{2\text{max}}$ is commonly attained. Nevertheless, it is important to note that these comparisons did not consider the eventual $\dot{V}\text{O}_{2\text{max}}$ dissimilarities among subjects of the different reported studies.

In addition, we have found lower τ values than those reported previously for 100 m front crawl (22.7 s; Rodriguez et al., 2003), being important to evidence that a specific distance performed at maximal intensity (i.e. with a “fast start”, as we have conducted) leads to inferior τ values than the same distance performed at an even pace (Jones et al., 2008). This faster $\dot{V}\text{O}_2$ kinetics is related with a shorter time lag in the unbalance of $\dot{V}\text{O}_2$ demand and supply, implying an augmented oxidative contribution to energy transfer (Burnley and Jones, 2007). Complementarily, the reported τ values were lower than those obtained for longer swimming distances (200 m; Sousa et al. (2011) and 400 m

front crawl; Rodriguez et al. (2003)), since this parameter mathematically describes the $\dot{V}O_2$ kinetics profile reflecting the response of cardiovascular and muscular systems at the selected intensity (Markovitz et al., 2004). Hence, the very high swimming intensity of the 100 m swim (implying the sudden and exponential need of $\dot{V}O_2$) justifies the observed lower τ values.

Regarding the energy requirement, different methodologies have been applied to estimate the energy sources. The aerobic contribution in swimming is traditionally evaluated by (i) directly measuring $\dot{V}O_2$ (Figueiredo et al., 2011; Ogita, 2006; Reis et al., 2010; Sousa et al., 2014; Troup, 1991), (ii) estimating $\dot{V}O_2$ based on $\dot{V}O_{2max}$ (Capelli et al., 1998; Zamparo et al., 2011) and (iii) measuring $\dot{V}O_2$ only during the recovery period using the backward extrapolation technique (Zamparo et al., 2000). In the current study we directly measured $\dot{V}O_2$, which presents the advantage of having “true” measured values rather than an indirect estimate, despite the minor constraints associated to the use of snorkel device with valve system. The aerobic requirement found in the present study was similar to the values reported for a 100 m (53%; Troup 1991 and 48%; Zamparo et al. 2000) and 1 min maximal front crawl swim (50%; Ogita 2006), but not in agreement with a 100-yard (33%; Capelli et al. 1998) and 100 m front crawl all-out efforts (69%; Reis et al. 2010). These discrepancies could be related to the distinct swimmer’s performance level to the different methodologies used to estimate the energy sources, and/or to the different lengths of the bouts. Considering the estimation of the anaerobic requirement, the used approach in the current study is considered valid and not affected by major errors (Capelli et al., 1998; Sousa et al., 2013), despite some questionable assumptions on the calculation of parameters regarding anaerobic contribution (e.g. the energy equivalent of lactate, working muscle mass). Moreover, this methodology takes into consideration anaerobic requirement partitioned by alactic and lactic energy sources, essential for the energy expenditure determination at very high intensity swimming. Hence, not accounting separately the anaerobic energy sources might result in an underestimation of energy expenditure, with impact on the understanding of

performance in short competitive events (Capelli et al., 1998; Figueiredo et al., 2011). On the contrary, the alternative methodology, based on the maximal accumulated oxygen deficit does not enable the alactic energy contribution assessment, and is a time consuming procedure (submaximal bouts are required) as well as supported by theoretical assumptions (e.g. linearity increase of O_2 demand with exercise intensity, constancy of O_2 from the onset of exercise), which contribute to some imprecision (Medbo, 1996; Reis et al., 2010). Regarding the above-referred studies, the anaerobic requirement was 31% (Reis et al., 2010), 48% (Troup, 1991), 50% (Ogita, 2006) assessed by means of maximal accumulated oxygen deficit. Using the same methodology of the current study, Zamparo et al. (2000) reported 52% of anaerobic requirement but only Capelli et al. (1998) computed separately the lactic and alactic contributions that were similar (19.6%) and higher (47.2%), respectively, compared to our data. In fact, some underestimation of the anaerobic demand could exist, probably related to task complexity constraints of the current study, particularly the impossibility to perform flip turns and starts that tends to decrease the average speed, thereby increasing the exercise duration. Nevertheless, comparing to a 200 m front crawl effort, both anaerobic lactic and alactic relative energy contribution (13.6 and 20.4%, respectively; Figueiredo et al., 2011) were lower than the current data, indicating that, despite in the same intensity domain, the anaerobic requirement was less important for the 200 m in comparison to the 100 m.

Studies that examined the energy cost assessment at the extreme intensity and in race-like swimming conditions are very scarce. Comparing to our results (both metabolic and mechanical energy cost estimations), elite male swimmers presented a superior energy cost value (1.73 kJ.m^{-1} , over a 91.4 m front crawl distance) at a superior velocity (1.75 m.s^{-1} ; Capelli et al. 1998), suggesting that swimming performances in short and very high intensity events are metabolic-dependent rather than exercise economy-dependent. Nevertheless, some caution in data interpretation should be taken, since different methodological procedures might slightly influence the energy cost values. In

fact, Zamparo et al. (2000) found higher energy cost values ($1.3 \text{ kJ}\cdot\text{m}^{-1}$) for young male swimmers during 100 m front crawl maximal swim at $1.50 \text{ m}\cdot\text{s}^{-1}$. However, taking as reference the energy cost at $\dot{V}\text{O}_{2\text{max}}$ intensity (~400m front crawl), our values were higher compared with those of highly trained swimmers ($0.61 \text{ kJ}\cdot\text{m}^{-1}$; Fernandes et al., 2006), possibly due to the higher anaerobic system contribution in the 100 m front crawl swim. Moreover, the known non-linear relationship between energy cost and swimming velocity indicates that minor increases in velocity leads to a substantial intensification of the energy cost (Wakayoshi et al., 1995).

As in swimming the lower limbs action is often considered more relevant for trunk balance, buoyancy and overall coordination than for propulsion (Gatta et al., 2012), we tested its influence over the very high swim intensity. It was possible to observe that $\dot{V}\text{O}_2$ kinetics during the S_{upper} presented a slower increase compared with the S_{full} condition as observed by the higher absolute τ values. An inverse association between $\dot{V}\text{O}_{2\text{peak}}$ and τ was identified (Zhang et al., 1991) but, when $\dot{V}\text{O}_2$ kinetics was scaled to $\dot{V}\text{O}_{2\text{peak}}$ values in each condition, the relative τ value was still higher in S_{upper} . This might be justified by the reduced cardiac output and/or a smaller arteriovenous O_2 content difference that lead to a delayed $\dot{V}\text{O}_2$ response when exercising only with the upper body (Koga et al., 1996; Pendergast, 1989). This delayed increase of the oxygen delivery to the working muscles would consequently lead to higher τ values, resulting in a glycolysis increase (Koga et al., 1996), which at the beginning of effort would required more energy from anaerobic sources, compromising the fatigue tolerance in the last stages of the exercise (Jones et al., 2008).

In fact, the $\dot{V}\text{O}_{2\text{peak}}$ in S_{upper} attained only 80% of the S_{full} condition, in accordance with the literature (Holmer, 1974; Ogita, 2006). Thus, the exercise intensity expressed as $\%\dot{V}\text{O}_{2\text{max}}$ could differ when using only the upper body in comparison to full body swimming, pointing out that training regimens should be developed taking into consideration these different metabolic profiles.

Complementarily, the lower relative anaerobic contribution found in S_{upper} could be explained, among other factors, by the lower muscle mass involved in the exercise (Sahlin and Henriksson, 1984). It is known that enhanced lactate release is provoked by a blood-flow reduction, especially to the upper limbs, when performing full body (Secher and Volianitis 2006). Moreover, and despite swimmers performed both 100 m bouts at maximal intensity, part of the interpretation of the higher relative aerobic energy release in S_{upper} condition could also be attributed to the longer time required to cover the same distance. In addition, the S_{upper} condition was more economical (~22%) than the S_{full} condition, most probably justified by the absence of lower limbs action (Ogita et al., 1996). Notwithstanding, it can be conjectured that lower limbs action could play an important role in the amount of aerobic energy liberated in the swimming bout, since it might enhance the acceleration of the cardiac output by decreasing the peripheral resistance for the cardiovascular system. Thus, it will enable a higher O_2 availability in all working muscles including those in the upper limbs, as suggested by the difference in τ for the condition involving lower limbs exercise or not. Moreover, it is important to note that swimming performance was ~14% higher when using the lower limbs, a gain previously referred for high velocities, probably due to propulsion intensification and wave drag reduction (Toussaint, 2011). Thus, bearing in mind that a 100 m event could be won by hundredths of a second, every added energy-supply and every minimal contribution to propulsion should be exploited rather than the promotion of swimming economy by limiting lower limbs action.

As the energy pathways contribution is time dependent and since S_{full} and S_{upper} presented distinct time durations, this might be considered as a possible limitation of the present study. Although, it should be highlighted that both conditions were performed at maximal intensity, which could be interpreted as a “relative maximum”, and fulfil the objective of analysing the influence of lower limbs in 100 m front crawl energetics. Moreover, it is important to state that only one transition from rest to effort was performed in each condition, which could lead to a low signal-to-noise ratio. Nonetheless, further studies to compare the

transient $\dot{V}O_2$ kinetics responses at extreme swimming intensity could be supported by the data from present study.

Conclusions

During extreme intensity swimming (100 m front crawl), an instantaneous and sudden increase of the $\dot{V}O_2$ occurred at the beginning of the exercise and continued to rise until the end of the bout, underlining the contribution of the aerobic energy pathway even in short and very intense swimming events. Nevertheless, taking into account that ~56% of total energy was obtained anaerobically both energy systems should be strengthened to improve the 100 m front crawl performance. Complementarily, when performing only with the upper body, the $\dot{V}O_2$ kinetics was slower, revealing the importance of the lower limbs action in providing a higher O_2 availability in all working muscles. Moreover, despite energy cost was higher to satisfy the superior energy requirements when using the lower limbs, performance improved ~14%.

Acknowledgment

This investigation was supported by grants of Portuguese Science and Technology Foundation: PTDC/DES/101224/2008 (FCOMP-01-0124-FEDER-009577) and SFRH/BD/81337/2011.

Ethical Standards

The experiments were approved by the local ethics committee, and performed according to the Declaration of Helsinki.

Chapter 8

How distinct level swimmers organise their biomechanics, energetics and coordination during extreme swimming intensity?

João Ribeiro^{1,2}, Pedro Figueiredo^{3,4}, Sara T. Morais², Francisco Alves⁵, Huub Toussain⁶, João P. Vilas-Boas^{1,2}, Ricardo J. Fernandes^{1,2}.

¹ Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal

² Porto Biomechanics Laboratory, University of Porto, Porto, Portugal

³ School of Physical Education, Federal University of Rio Grande do Sul

⁴ Department of Kinesiology, University of Maryland

⁵ Faculty of Human Movement Technical University of Lisbon, Lisbon, Portugal

⁶ Amsterdam University of Applied Sciences, School of Sports and Nutrition, Amsterdam, Netherlands

Submitted for publication on Journal of Sports Sciences.

Abstract

Our purpose was to examine how distinct level swimmers organise their biomechanics, energetics and coordination throughout an extreme intensity swim. Sixteen male swimmers (eight high and eight low-speed swimmers) performed 100 m front crawl at maximal intensity. Then accomplished 25, 50 and 75 m bouts (90 min rest) at the same pace as the previous 100 m bout and 100 m maximal front crawl on the measuring active drag system. A 3D dual media optoelectronic system (eight under water and seven land cameras) was used to assess speed, stroke frequency, stroke length, propelling efficiency and index of coordination, with power assessed by the measuring active drag system and energy cost by quantifying oxygen consumption plus blood lactate. Both groups presented a similar profile in speed, power output, stroke frequency, stroke length, propelling efficiency and energy cost along the extreme intensity swim, while a distinct coordination profile was observed ($F_{(3, 42)} = 3.59$, $p = 0.04$). The speed, power, stroke frequency and propelling efficiency values were higher in high-speed swimmers, while stroke length and energy cost were similar between the two groups. Performing front crawl at extreme intensity will lead better level swimmers to achieve superior speed due to their higher power output and a tendency for superior propelling efficiency, with consequent ability to swim at higher stroke frequencies. This imposes specific constraints along the exercise, resulting in a distinct adaption of motor organization, occasioning a different index of coordination profile between groups.

Key words: Kinematics, power, propelling efficiency, coordination, energy cost, front crawl

.

Introduction

Competitive swimmers' goal is to perform as fast as possible in a specific event. To accomplish that it is required a certain mechanical power output (P_o) that depends on metabolic power input (\dot{E}) and on overall efficiency of locomotion (η_o): $P_o = \dot{E} \cdot \eta_o$ (Toussaint and Hollander, 1994; Zamparo and Swaine, 2012). \dot{E} depends on aerobic, anaerobic lactic and alactic energy pathways, while η_o results from the ratio between the total mechanical work per unit of distance (W_{tot}) and the energy cost of exercise (C): $\eta_o = W_{tot}/C$. For a given η_o , C can be compromised since not all the total mechanical work is used for propulsion, with the portion of W_{tot} that is transformed into useful work to overcome drag (W_D) being given by propelling efficiency (η_P): $\eta_P = W_D/W_{tot}$ (Toussaint and Hollander, 1994; Zamparo, 2006; Zamparo et al., 2008). But other than that, swimming speed and, consequently, C are not only dependent on η_P , but also on the timing between the swimmers' propulsive actions and its frequency (stroke frequency, SF; Chollet et al., 2000; Seifert et al., 2015). SF results from the ratio of swimming speed and the distance the swimmer's body moves through the water in each swimming cycle (SL; Craig et al., 1985): $SF = \text{speed}/SL$.

The aforementioned theoretical background reveals that swimming performance depends on several factors, varying significantly with swimmers competitive level. In fact, the best performance of higher-level swimmers can result from an optimal SF and SL combination, enabling an inter-limb coordination mode that minimizes the time gap between propulsive phases (Chollet et al., 2000; Lerda and Cardelli, 2003; Seifert et al., 2007). This seems to be a fine solution to produce sufficient propulsion to overcome the consequent superior drag, but not necessarily warranting a higher η_P (Seifert et al., 2015). Indeed, for higher swimming speeds, superior P_o and \dot{E} are required, while η_P is expected to decline, compromising swimming economy and leading to C increase (Fernandes et al., 2006; Seifert et al., 2010a; Seifert et al., 2010b).

In this context, despite some studies have already provided valuable information on the relationship among the aforementioned factors in distinct swimmers' levels (eg. Cappaert et al., 1992; Lerda and Cardelli 2003; Seifert et al. 2010a), their methodological approach focused mainly on non-competitive swimming scenarios, missing the analysis of biomechanical, bioenergetical and coordinative performance determinants during competitive distances. Moreover, swimming performance at extreme intensities was never assessed using a comprehensive biophysical approach, existing a shortage of quantitative data particularly at competitive paces. As the 100 m freestyle is the swimming event that better represents performance at this intensity domain (effort ~1 min duration), we aimed to examine how distinct performance level swimmers organise selected biomechanical, energetic and coordinative factors throughout an extreme intensity swim.

Methods

Subjects

Sixteen voluntary male swimmers were divided in two performance level groups. Their main characteristics are: 21.12 ± 3.31 vs. 18.63 ± 1.60 years of age, 1.79 ± 0.03 m vs. 1.77 ± 0.03 m of height, 73.94 ± 6.42 vs. 69.12 ± 2.53 kg of body mass, $115.24 \pm 4.29\%$ vs. $124.39 \pm 3.37\%$ of 100 m freestyle world record time for high ($n = 8$) low-speed ($n = 8$) groups, respectively. Participants (or parent/guardian when subjects were under 18 years old) provided informed written consent before data collection and avoided strenuous exercise, and abstained from smoking and consuming alcohol or caffeine 48 h prior to testing. Swimmers were previously familiarized with the experimental equipment and procedures that were approved by the local ethics committee and performed according to the Declaration of Helsinki.

Experimental design

The test sessions took place in a 25 m indoor pool (1.90 m deep) with a water temperature of 27.5 °C and 60% of air humidity. Each subject performed, in free-swimming condition, 100 m front crawl at maximal intensity. Secondly, to determine the parameters that could not be assessed during 100 m bout test, swimmers accomplished: (i) 25, 50 and 75 m front crawl bouts (with 90 min active rest interval) at the same swimming speed (controlled by a visual light pacing system placed in the bottom of the pool with a flash every 5 m; Pacer2Swim OEM Kulzer TEC, Aveiro, Portugal) as in the previous 100 m test; and (ii) after 24 h rest, 100 m front crawl at maximal intensity on the measuring active drag system (MAD-system; Toussaint et al., 1988) using only the upper limbs (the lower limbs were supported by a standard pull-buoy). All test sessions were preceded by an individual warm-up consisting on 15 min of low to moderate intensity and 10 min passive rest was taken between warm-up and exercise bouts (to ensure that previous workout did not influence exercise tolerance; Bailey et al., 2009). In-water starts and open turns (without gliding) were always used eliminating the influence of the dive and gliding in the analysis of swimming cycle.

Data collection and analysis

Biomechanics

Kinematics parameters were assessed using seven land plus eight underwater cameras (Oqus 3+ and Oqus Underwater, Qualisys AB, Gothenburg, Sweden) operating at 60 Hz. The calibrated volume was defined using under water, above the water and twin to merge the first and the latter (according to the manufacturer's guidelines) calibrations. This enabled the creation of 3D dual media working volume, where the orthogonal axes were defined as x for horizontal, y for the mediolateral and z for vertical ($z = 0$ defines the water surface) movements, respectively. Data acquisition was performed with Qualisys Track Manager version 2.7 (Qualisys AB, Gothenburg, Sweden).

Each swimmer was equipped with upper body retroreflective markers, with the acromion, lateral and medial humerus epicondyle, radius- and ulna-styloid processes, third distal phalanx, iliac crest and anterior and posterior iliac spine (for both right and left body sides) selected as anatomical landmarks. Data post-processing employed Visual3D (C-Motion, Germantown, MD, USA) using a low pass digital filter of 6 Hz. SF of each 25 m lap was assessed by the inverse of the time needed to complete one front crawl cycle (defined as two consecutive water entries of the same hand) at the middle of the pool (clean velocity) and SL was obtained by the horizontal displacement of the centre of mass (CM, pelvis). Swimming speed was computed by dividing the horizontal displacement of the CM by the time required to complete one front crawl cycle. For the pooled sample (combining high and low-speed swimmers), the mean speed variation (Δv) was assessed by the difference in mean speed between the last and first laps. Hand speed was computed as the sum of the instantaneous 3D speed of the right and left hands during the underwater phase and η_P was estimated from the CM speed to 3D mean hand speed (Figueiredo et al., 2011).

In the MAD-system condition, swimmers pushed-off from fixed pads (1.35 m apart) attached to a 23 m rod at 0.8 m below water surface, which was instrumented with a force transducer allowing measuring the push-off force from each pad. The force signals were acquired by an A/D converter (BIOPAC Systems, Inc.) at a sample rate of 1000 Hz and filtered with a low pass digital filter with a cut-off frequency of 10 Hz (Ribeiro et al., 2013). For each performance level group the P_o of each lap was calculated as the product of the mean speed and the mean force of the lap. For the pooled sample, the mean P_o variation (ΔP_o) was assessed by the difference in P_o between the last and first laps.

Energetics

Oxygen uptake ($\dot{V}O_2$) was directly and continuously measured using a telemetric portable gas analyser (K4b², Cosmed, Rome, Italy) connected to a

specific respiratory snorkel and valve system (Aquatrainer, Cosmed, Rome, Italy). This snorkel is a breath-by-breath low hydrodynamic resistance device (Baldari et al., 2013; Ribeiro et al., 2015a) that allows swimming front crawl without restrictions. Capillary blood samples for lactate concentration ($[La^-]$) analysis were collected before and after all bouts (at 1, 3, 5 and 7 min) using a portable lactate analyser (Lactate Pro, Arkray, Inc., Kyoto, Japan).

Energy systems contribution were determined, for each 25 m lap, as follows: (i) the aerobic participation was assessed from the time integral of the net $\dot{V}O_2$ versus time relationship; (ii) the anaerobic contribution was obtained considering the sum of the energy derived from lactic acid production with the one derived from phosphocreatine splitting in the contracting muscles (Figueiredo et al., 2011; Ribeiro et al., 2015b; Sousa et al., 2014):

$$AnL = \beta \times [La]_{net} \times M \quad (1)$$

where $[La]_{net}$ is the difference between the blood lactate accumulation after and before exercise, β is the energy equivalent for blood lactate accumulation ($2.7 \text{ ml O}_2 \cdot \text{mM}^{-1} \text{ kg}^{-1}$; di Prampero et al. 1978) and M is the mass of the subject. $[La]_{net}$ was calculated as the difference in $[La]_{basal}$ before and after each lap: $[La]_{net25} = [La]_{basal25} - [La]_{rest}$, $[La]_{net50} = [La]_{basal50} - [La]_{basal25}$, $[La]_{net70} = [La]_{basal75} - [La]_{basal50}$ and $[La]_{net100} = [La]_{basal100} - [La]_{basal75}$ for the first, second, third and fourth laps (respectively); (iii) The anaerobic alactic contribution (AnAl) was obtained using the following equation (Capelli et al., 1998; Figueiredo et al., 2011; Ribeiro et al. 2015b):

$$AnAl = PCr \left(1 - e^{\left(-\frac{t}{\tau} \right)} \right) \times M \quad (2)$$

where t is the time duration, τ is the time constant of phosphocreatine splitting at work onset (23.4 s; Binzoni et al., 1992), M is the mass of the subject and PCr is the phosphocreatine concentration at rest assumed to be $18.5 \text{ mmol} \cdot \text{kg}^{-1}$

(Capelli et al., 1998; Ribeiro et al., 2015b; Zamparo et al., 2011). The energy derived from the utilization of the phosphocreatine stores was estimated assuming that, in the transition from rest to exhaustion, its concentration decreases by $18.5 \text{ mmol.kg}^{-1}$ (wet weight) in maximally active muscle assumed to correspond to 30% of body mass.

Anaerobic alactic contribution for each lap was calculated as the difference in AnAl before and after each 25 m: $\text{AnAl } 25 = \text{AnAl } 25 - \text{AnAl rest}$, $\text{AnAl } 50 = \text{AnAl } 50 - \text{AnAl } 25$, $\text{AnAl } 75 = \text{AnAl } 75 - \text{AnAl } 50$ and $\text{AnAl } 100 = \text{AnAl } 100 - \text{AnAl } 75$ for the first, second, third and fourth laps (respectively). To express different energy sources in the same units (kJ), the anaerobic alactic contribution was converted to kJ assuming a phosphorus/oxygen ratio of 6.25 and a energy equivalent of $0.468 \text{ kJ.mmol.kg}^{-1}$ (Capelli et al., 1998), while for the aerobic energy contributions the energy equivalent was $20.9 \text{ kJ.lO}_2^{-1}$ (Figueiredo et al., 2011; Ribeiro et al., 2015b; Sousa et al., 2014). Based on this overall data, energy expenditure was assessed and C was obtained as the ratio between energy expenditure rate and mean speed (Fernandes et al., 2006).

Coordination

For coordination data analysis, front crawl upper limbs movements were split into four phases, determined from the swimmer's x and z positions of the hand CM and acromion (Chollet et al., 2000): (i) entry and catch, between the first z negative coordinate and the beginning of the backward movement of the hand CM; (ii) pull, from the end of the entry and catch phase until the mid-underwater position, determined by coincident x positions of hand CM and acromion; (iii) push, from the end of the pull until the hand release from the water, determined by the z positive coordinate of hand CM after the underwater trajectory; and (iv) recovery, from the end of the push until re-entry of the hand CM. Upper limbs coordination was quantified using the index of coordination (IdC), measuring the lag time between the propulsive phases of the limbs actions, expressed as the percentage of the overall duration of the front crawl cycle that

can shift from catch-up ($IdC < 0\%$) to opposition ($IdC = 0\%$) and superposition ($IdC > 0\%$) modes (cf. Chollet et al. 2000).

Statistical analysis

Standard statistical methods were used to calculate mean and standard deviation (SD) and normal Gaussian data distribution was verified using the Shapiro-Wilks test. A two-way ANOVA [lap x performance level] was used to compare changes in the studied variables along the 100 m effort, with Sphericity (homogeneity of variance and covariance) verified by means of the Mauchley test. If the assumption of sphericity was not met, the significance of the F-ratios was adjusted according to the Greenhouse-Geisser procedure. When a significant F value was achieved, Bonferroni post hoc procedures were performed to locate the pairwise differences between the means. Cohen's f was used to compute the effect size considering that 0.1 are small, 0.3 moderate and 0.5 large, 0.7 very large and 0.9 extremely large (Hopkins et al., 2009). The relationship between Δv and ΔP_o was analysed through Pearson correlation test and to determine the 25, 50, and 75 m tests reliability between the different simulated swims, a one-way repeated measures ANOVA was used. A SF reliability was found for the first ($F_{(3,15)} = 1.51$, $p = 0.11$, $f = 0.29$), second ($F_{(2,30)} = 0.50$, $p = 0.61$, $f = 0.18$) and third laps ($F_{(1,15)} = 2.41$, $p = 0.09$, $f = 0.30$), as well as for rest [La^-], ($F_{(3,27)} = 0.34$, $p = 0.80$, $f = 0.13$). For all tests, the level of significance was set at 5%.

Results

High-speed swimmers completed the front crawl maximal 100 m effort at a faster mean speed than the low-speed counterparts ($F_{(1,14)} = 18.26$, $p = 0.001$, $f = 1.33$) both when swimming freely (1.48 ± 0.05 vs 1.33 ± 0.07 m.s⁻¹) and on the MAD-system (1.64 ± 0.06 vs 1.49 ± 0.10 m.s⁻¹). However, both groups presented the same speed ($F_{(1.90, 26.60)} = 0.11$, $p = 0.73$, $f = 0.62$; Figure 1 left panel) and P_o profiles ($F_{(1.82, 25.42)} = 1.17$, $p = 0.33$, $f = 0.29$; Figure 1 right

panel), decreasing from the first to the last lap of the 100 m effort ($F_{(1.90, 26.60)} = 36.09$, $p < 0.001$, $f = 0.62$ and $F_{(1.82, 25.42)} = 26.36$, $p < 0.001$, $f = 1.36$, respectively). Furthermore, in every 25 m, high-speed swimmers presented superior speed ($F_{(1, 14)} = 13.82$, $p = 0.002$, $f = 1.00$) and P_o ($F_{(1, 14)} = 4.34$, $p = 0.05$, $f = 0.56$). Considering the pooled sample, Δv (first and last lap: $1.66 \pm 0.10 - 1.37 \pm 0.10 \text{ m.s}^{-1}$) presented a high positive relationship with ΔP_o (first and last lap: $116.12 \pm 33.35 - 84.71 \pm 24.01 \text{ W}$) ($r = 0.84$, $p < 0.001$), corresponding to approximately 21 and 23% decrease (respectively).

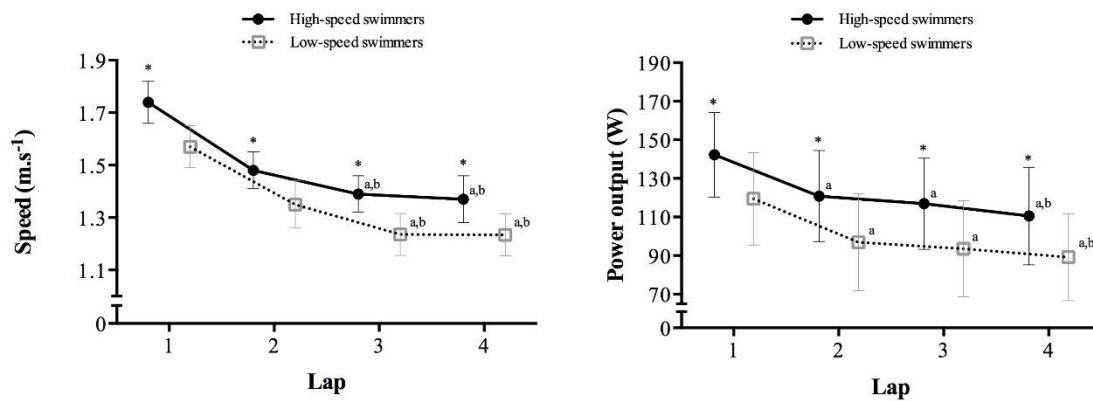


Figure 1. Mean (\pm SD) values of speed and power output (left and right panels, respectively) for high and low-speed swimmers in each 25 m lap of the free 100 m maximal effort.

The general swimming kinematics behaviour along the four 25 m laps (Figure 2, left panel) evidenced no interaction effect (same profile) for SF ($F_{(1.94, 27.12)} = 0.60$, $p = 0.55$, $f = 0.20$) and SL ($F_{(3, 42)} = 0.89$, $p = 0.45$, $f = 0.25$). High-speed swimmers presented superior SF ($F_{(1, 14)} = 14.46$, $p = 0.002$, $f = 1.02$) and similar SL ($F_{(1, 14)} = 0.93$, $p = 0.35$, $f = 0.26$) values compared with low-speed swimmers in the four laps. In both groups SF decreased from the first to the third lap and increased in the fourth ($F_{(1.94, 27.12)} = 14.99$, $p < 0.001$, $f = 1.04$), whereas SL was stable in the first three partials and decreased on the fourth lap ($F_{(3, 42)} = 8.51$, $p < 0.001$, $f = 0.78$). The pooled sample pattern for SF between free swimming and MAD-system conditions were similar since no [lap x swimming condition] interaction effect was observed ($F_{(2.04, 59.22)} = 0.52$,

$p = 0.60$, $f = 0.14$) and no normalised SF differences ($F_{(1, 30)} = 3.46$, $p = 0.07$, $f = 0.33$) were evidenced (Figure 2, right panel).

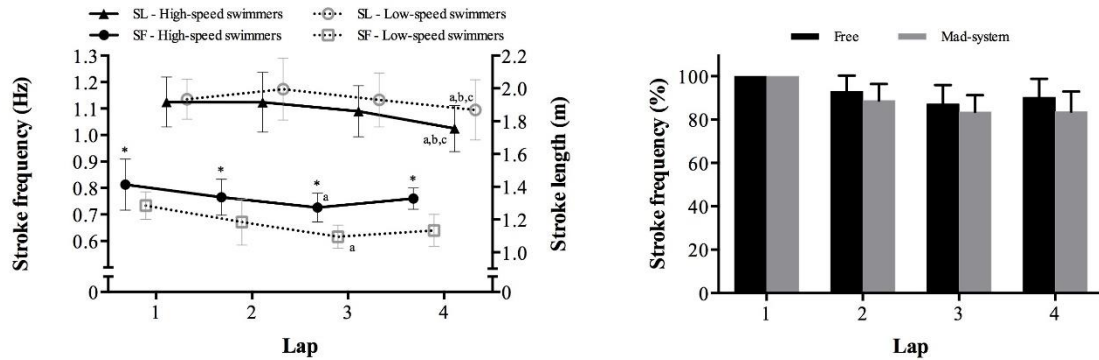


Figure 2. Mean (\pm SD) values of stroke frequency (SF) and stroke length (SL) values for high and low-speed swimmers in each 25 m lap of the free 100 m maximal effort (left panel). The normalised SF of the pool sample is also presented during unimpeded and MAD-system (black and grey bars, respectively) conditions (right panel).

Both groups of swimmers remained in catch-up coordination mode, but presented distinct IdC profiles throughout the effort, as a [lap x group] interaction effect was observed ($F_{(3, 42)} = 3.59$, $p = 0.04$, $f = 0.59$). High-speed swimmers presented superior IdC ($F_{(1, 14)} = 6.01$, $p = 0.04$, $f = 0.60$) than the low-speed ones (with exception of first lap), maintaining it in the second partial and increasing the values in the last two laps. On the other hand, low-speed swimmers decreased the IdC from the first to second lap, and increased it from this partial to the fourth lap ($F_{(3, 42)} = 10.97$, $p < 0.001$, $f = 0.79$).

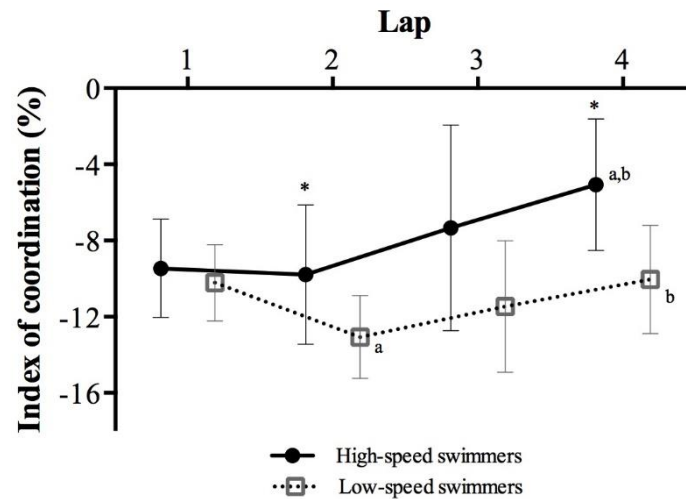


Figure 3. Mean (\pm SD) values of index of coordination values for high- and low-speed swimmers in each 25 m lap of the free 100 m maximal effort.

High- and low-speed swimmers presented the same η_P ($F_{(3, 42)} = 0.30$, $p = 0.83$, $f = 0.14$) and C profiles ($F_{(1.82, 25.42)} = 1.17$, $p = 0.33$, $f = 0.29$) along the 100 m front crawl effort, remaining stable ($F_{(3, 42)} = 3.72$, $p = 0.06$, $f = 0.52$; Figure 4, left panel), while C was maintained until the third lap followed by an increased in the fourth 25 m ($F_{(3, 42)} = 4.63$, $p = 0.007$, $f = 0.58$; Figure 4, right panel). High-speed swimmers presented a tendency for superior η_P ($F_{(1, 14)} = 3.32$, $p = 0.09$, $f = 0.48$, only significant for $p < 0.09$ but with clinical and practical importance), while C was similar between groups ($F_{(1, 14)} = 0.02$, $p = 0.90$, $f = 0.03$).

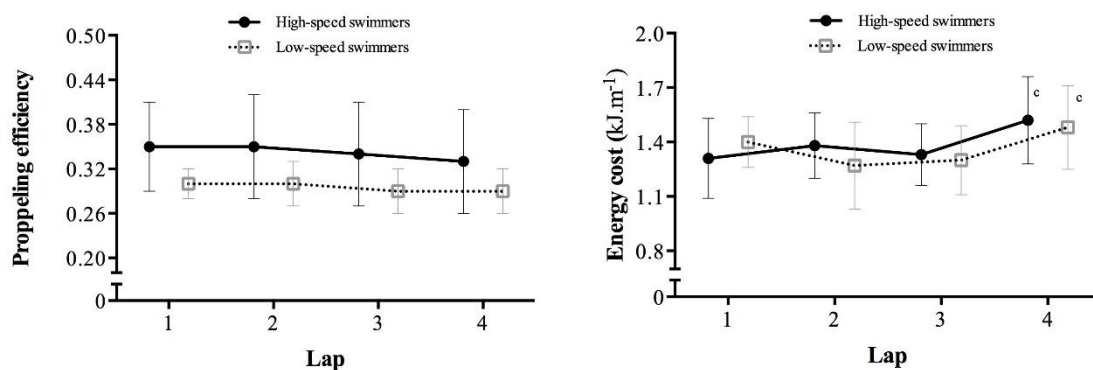


Figure 4. Mean (\pm SD) values of propelling efficiency and energy cost values (left and right panels, respectively) for high and low-speed swimmers (circles and squares, respectively) in each 25 m lap of the free 100 m maximal effort.

Discussion

The purpose of the current study was to analyse how different performance level swimmers organise selected biomechanical, energetic and coordinative factors throughout an extreme swim effort. As main findings, high- and low-speed swimmers presented an equivalent profile in the 100 maximal front crawl speed, P_o , SF, SL, η_P and C. Nevertheless, high-speed swimmers were faster due to their superior P_o and η_P , with consequent ability to swim at a superior SF, leading to a higher IdC compared to the lower-speed counterparts. Swimming speed declined along the extreme intensity effort in accordance with the literature (Chollet et al., 1997; Seifert et al., 1995; Toussaint et al., 2006; Vorontsov and Binevsky, 2003), but it was not influenced by swimmers' level, as both groups presented the same profile and percentage decrease. This could be explained by the fact that all-out efforts presuppose a faster-speed starting that necessarily decreases throughout the exertion time. Consequently, shorter duration efforts imply less margin for the adoption of a pacing strategy compared to longer competitive swimming distances (Craig et al., 1985; Maglischo, 2003). In spite of the same speed profile, high-speed swimmers were faster along the four 25 m laps, due to their greater capacity to generate power (Sharp et al., 1982; Toussaint et al., 2006), as observed by the direct relationship between Δv and ΔP_o .

Both high- and low-speed swimmers exhibited a reduction in SF until the third lap, followed by an increase in the fourth to compensate the decrease in SL. This is a common finding in the last moments of swimming events, when the swimmers strive to maintain speed (Chollet et al., 1997; Seifert et al., 2005; Seifert et al., 2007; Toussaint et al., 2006; Vorontsov and Binevsky, 2003). Notwithstanding both groups presented the same profile, high-speed swimmers were able to achieve superior SF along the effort imposed by the higher P_o (dependent on work per stroke times SF) and, consequently, higher swimming speed (Chollet et al., 1997; Seifert et al., 2007).

While swimming speed and SF reduced along the effort, SL was maintained stable (with the exception of the decline in the last stage) in both groups. This supports the assumption that the decay in swimming speed affects less SL and mainly SF, which might serve as a better indicator of power production loss (Toussaint et al., 2006; Vorontsov and Binevsky, 2003). Literature have been pointing out an SL maintenance throughout extreme intensity efforts in high skilled swimmers (Chollet et al., 1997; Seifert et al., 2005; Seifert et al., 2007; Toussaint et al., 2006), while a substantial decrease has been observed in the less skilled ones (Chollet et al., 1997; Seifert et al., 2007), but the current groups presented the same SL profile. This parameter is linked to swimming speed and SF, and since the pattern of these variables was similar in high- and low-speed swimmers, the same SL profile was also expected. In addition, the inverse relationship between SL and speed explains why high-speed swimmers, performing at superior speeds, presented the same SL magnitude as the low-speed ones.

During swimming P_o is hard to assess and so, in the present study, it was assumed to be similar to the obtained using the MAD-system. To support this assumption some considerations can be put forward: (i) the equivalent relative SF decrease in each 25 m lap when comparing the free swimming vs MAD-system condition; (ii) the same relative speed and P_o declines; and (iii) the observed association between these two variables. Moreover, previous electromyographic measurements during unimpeded and MAD-system swimming conditions revealed that muscular activation patterns are similar (Clarys et al., 1988). It should be stated, though, that swimmers used their lower limbs in unimpeded condition and so an underestimation ranging from 9.8 to 37.8 W of P_o measured in MAD-condition could occur (Hollander et al., 1988). The higher speed on the MAD-system compared to free swimming is due to the power expended giving the water a change in kinetic energy during free condition.

Along the 100 m effort, high- and low-speed swimmers presented the same P_o profile, mirroring the swimming speed pattern. In fact, these two parameters are highly related and so the superior speed presented by the high-speed swimmers might be due to their greater capacity to generate P_o . This fact corroborates previous studies in which a high relationship between P_o (obtained in laboratory, not swimming pool) and sprint swimming performance was observed (Hawley and Williams, 1991; Hawley et al., 1992; Sharp et al., 1982). Despite the superior P_o achieved by high-speed swimmers, both groups presented the same relative reduction of this parameter along the exercise, in accordance with previous findings in experienced swimmers (~24%), for the same distance (Toussaint et al., 2006). This decline led to a decrease in swimming speed and, consequently, in SF, suggesting that P_o and SF seem to be the best discriminative factors of an extreme intensity swim (Lätt et al., 2010; Toussaint et al., 2006).

High-speed swimmers presented higher coordination pattern variability than the low-speed counterparts, substantially increasing IdC along the effort. This fact could be interpreted as an effective way to deal with fatigue, compensating the reduction in P_o generating ability (Alberty et al., 2005). In fact, P_o decline along the laps affects SF, leading high-speed swimmers to gradually adapt the motor organization (by minimizing the time gap between propulsive phases) to maintain their superior speed (Chollet et al., 2000). As it is known that swimming technique must be sufficiently flexible and adaptable to enable emerging patterns of coordination to be modified according to constraints (Glazier et al., 2006), high-speed swimmers' coordination pattern variability can be interpreted as a functional property that helps them to adapt the movement behaviours according to performance constraints (Davids et al., 2008; Glazier et al., 2006; Seifert et al., 2014).

Complementarily, high-speed swimmers were capable to achieve superior IdC values along the swim (with exception of first moment), in accordance with the literature that reveals that faster swimmers present a less negative IdC than the

slower ones (Chollet et al., 2000; Lerda and Cardelli, 2003; Seifert et al., 2007). This is justified by the fact that faster swimmers present higher P_o and, consequently, higher maximal speed, more drag resistance and superior SF and, since low-speed swimmers present a lower SF, their glide could be favoured and IdC maintained in a more negative value (Bideault et al., 2013).

Despite the differences in IdC values, both groups remained in catch-up coordination mode throughout the 100 m effort, in line with the values found for a longer but still extreme swimming intensity (200 m front crawl; Figueiredo et al 2011), but is at odds with studies where a superposition coordination model was reported (Seifert et al., 2005; Seifert et al., 2007). These differences may warrant some caution in its interpretation since: (i) swimmers of distinct levels can present dissimilar IdC values and (ii) different methodological procedures in IdC determination (kinematical data vs visual inspection) may influence the outputs.

Concerning η_P , its pattern on both groups remained approximately constant (with non-significant 3-5% decrease) throughout the effort, corroborating the literature (Toussaint et al., 2006). Considering the theoretical basis, it was expected that η_P mirrored SL, decreasing also in the last stages. The absence of this occurrence could be explained by the fatigability experienced along the effort, leading to a reduction in hand speed (4.94 ± 0.37 , 4.68 ± 0.37 , 4.39 ± 0.38 , 4.35 ± 0.39 m.s⁻¹ for first, second, third and fourth lap, respectively) concomitant with speed decrease, which allows η_P maintenance. Comparing current data to a 200 m front crawl maximal effort (Figueiredo et al., 2011), elite swimmers were able to maintain η_P until the third part (i.e. 150 m), but a reduction in the last lap was observed, suggesting that, despite the superior pace of the 100 m effort, its short duration could enable η_P conservation. In fact, due to the high speeds achieved in the 100 m effort, η_P was lower from the very beginning and so, it was also easier to sustain throughout the exercise.

The η_P is commonly considered a discriminative skill factor (Zamparo, 2006; Zamparo et al., 2008), but in the current study no differences in η_P patterns of the two groups were observed. Nonetheless, high-speed swimmers presented a tendency for superior η_P along the effort, probably due to their greater technical skill. It should be taken into account, though, that the methodology to assess is limited to a ratio swimming/hand speed, neither considering technical aspects responsible for propulsion (like hand and forearm orientation essential to pointing lift and drag forces in a favourable direction) nor thrust-producing vortices (Triantafyllou and Triantafyllou, 1995). Notwithstanding, it can be conjectured that high-speed swimmers performing with superior hand velocities (mean 100 m effort: 4.74 ± 0.42 vs 4.43 ± 0.41 m.s⁻¹ for high and low speed swimmers, respectively) were able to create higher propulsion-enhancing outcome as a result of a strong axial flow component along the rotating upper limb: the “pumping effect” (cf. Toussaint et al., 2002).

The C values reported in this study are compatible with values found in the literature for the same effort (Ribeiro et al., 2015b; Zamparo et al., 2000). However, it was expected that high-speed swimmers presented superior C due to their higher speed, explained by the non-linear relationship between C and swimming speed, which presupposes that minor increases in speed leads to a substantial intensification of C (Wakayoshi et al., 1995). However, considering that the superior speed achieved by faster swimmers also imply greater available energy (Fernandes et al., 2006), specially in short swimming events where the task-goal is to swim as fast as possible, the ratio energy expenditure/speed was probably maintained along the four laps, being similar to the low-speed swimmers (but with higher absolute value of energy expenditure and speed). This is consistent with the influence of energy expenditure and drag on C, with high-speed swimmers showing higher energy expenditure and expected higher drag, leading to similar C values as their slower counterparts.

In both groups C was maintained during the effort, with the exception of last stage where an increase was observed. Some assumptions can be put forward

to support this raise in the last moment, considering that C main determinants are η_P and hydrodynamic resistance (Zamparo et al., 2008). In one hand, a slight diminishment of η_P could occur considering that SL also decreased and, on the other hand, drag could have increased, despite the decay on speed. This is justified considering that as the speed decreases, swimmers' bodies tend to adopt a less streamline position and trunk inclination becomes critical (particularly at speeds lower than 1.4 m.s^{-1} , Zamparo et al., 2009) and also because some deterioration on swimming technique could appear at the end of effort, as swimmers become fatigued and higher lactate accumulation occurs (Toussaint et al., 2006; Wakayoshi et al., 1995).

Conclusion

During an extreme intensity swim, the mode that high- and low-speed swimmers organise the general biomechanical parameters, P_o , η_P and C seems not to discriminate their differences in final performance. However, high-speed swimmers are characterized by greater values of P_o and a tendency for superior η_P (with consequent higher SF), leading to a distinct coordination profile along the effort. The monitoring and development of these parameters through specific training practices should be contemplated as an approach to optimise performance of extreme front crawl swimming intensity.

Acknowledgment

This investigation was supported by grants of Portuguese Science and Technology Foundation: PTDC/DES/101224/2008 (FCOMP-01-0124-FEDER-009577) and SFRH/BD/81337/2011.

Ethical Standards

The experiments were approved by the local ethics committee, and performed according to the Declaration of Helsinki.

Chapter 9 General Discussion

The comprehension of aquatic locomotion requires deep understanding of multiple scientific domains from basic biology and engineering to performance in aquatic sports. As peak performance in swimming requires a profound adaptation to the aquatic environment that places special demands on the swimmer, the specificity of training and testing in swimming is very important (Keskinen and Keskinen, 1999; Maglischo, 2003; Olbrecht, 2000; Wilmore and Costill, 1999). Considering that the current Thesis focused on the identification and characterisation of biophysical front crawl swimming performance determinants at different intensities, it were our aims to: (i) biophysically analyse the front crawl technique, which is the conventional technique most used in training and competition, and the fastest known form of human aquatic locomotion; (ii) conduct all experimental procedures in ecological swimming conditions; (iii) assess the front crawl biomechanical and energetic determinants along the entire exercise duration; (iv) analyse concurrently biomechanical and energetic parameters in the global range of exercise intensity (low-moderate to extreme domains); and (v) ensure the minimal influence of testing equipment on swimmers final performance.

Studies focusing on the examination of swimmers locomotion based on biomechanical factors often include the analysis of swimming kinematics to understand and improve the consequent physiological behaviour (Barbosa et al., 2010a). To accomplish this, kinematics of a fixed point (usually the hip) is commonly used rather than the CM (Alberty et al., 2005; Craig et al., 2006; Gourgoulis et al., 2014; Schnitzler et al., 2010), since it is a much more simple methodology. When comparing the kinematic profiles of the hip and CM in front crawl technique (**Appendix I**), data showed similar mean values for both forward velocity and displacement, at the velocity corresponding to the AnT (moderate intensity domain). This was in line with previous studies and justified by CM localization in the pelvic region that is not expected to change significantly in alternated swimming techniques (Costill et al., 1987; Figueiredo

et al., 2009). In this sense, it was suggested that hip front crawl kinematics assessment is a reliable procedure and that the evaluation of relevant performance kinematics using this body point could be more precise than CM, when analysing the balance between swimming propulsive and resistive forces (since the latter tends to vary according with the breathing pattern and the distribution of body fluids; Bartlett, 2007).

Swimming at steady state conditions presupposes a balance between the average forward propulsion from body segments motion and average drag acting on swimmer's body (the higher the swimming velocity, the greater the hydrodynamic resistance). As an increase in velocity requires an amplification of applied muscle force, resulting in an intensification of propulsion (Vorontsov, 2011), propulsive hydrodynamics forces in front crawl have been considered as a main performance determinants that depend on other biomechanical factors (Toussaint, 2011). Taking this into account, the relationships between force and general stroking parameters (velocity, SF and SL), IVV, IdC and η_P were examined (**Chapter 2**). We observed that higher force production required increases in SF and velocity (Berger et al., 1999; Martin et al., 1981; Toussaint et al., 1988) and, consequently, SL and η_P presented a negative relationship with force production since these parameters are inversely related with SF (Barbosa et al., 2010b). This agrees with literature (Keskinen and Komi, 1993; Psycharakis et al., 2008; Seifert et al., 2010b) and corroborates the findings that swimmers reach higher velocities by increasing SF and decreasing SL and, consequently, η_P (as observed later in **Chapter 8**). Moreover, the observed inverse relationship between force and IVV revealed the importance of propulsive continuity to achieve higher values of force production (Figueiredo et al., 2013a) corroborated by the concomitant increase of IdC as force augmented (Seifert and Chollet, 2009).

As the ability to generate high levels of force, power and SF are directly related to the liberation of metabolic power, assessing energetics is also fundamental to the understanding of swimming locomotion (Barbosa et al., 2010a; Pendergast

et al., 2006; Pyne and Sharp, 2014). For that purpose, respiratory snorkels enabling the collection of expired gases are frequently used (Gayda et al., 2010; Keskinen et al., 2003; Toussaint et al., 1987) and, as recently an up to date version was developed we evaluated the validity of its application by measuring real time gas analysis under controlled laboratory and swimming pool conditions (**Appendix II**). A high agreement regarding ventilatory parameters was observed, contrary to previous results that reported systematic differences of other snorkels models comparing with the standard mask (Gayda et al., 2010; Keskinen et al., 2003) or with a gas exchange simulator (Rodriguez et al., 2008), suggesting that the new AquaTrainer® snorkel is a useful device for oxygen uptake assessment in swimming.

Another concern when using breathing snorkels to assess swimming energetics is that the device may compromise the swimmer's drag both during stroking and gliding, being also important to test its eventual added hydrodynamic drag (**Chapter 3**) to ensure ventilatory data validity (Toussaint et al., 1987). We observed that the AquaTrainer® snorkel had no drag effect for a wide range of swimming intensities, as previously observed for other breathing apparatus (Dal Monte et al., 1994; Toussaint et al., 1987), confirming that evaluating aerobic energetics using a snorkel does not lead to significant additional drag during swimming. Moreover, as swimming front crawl using the snorkel does not enable performing the traditional tumble turn technique, selected during competition and in training conditions, the constraint of using an adapted turning technique was also evaluated (**Chapter 3**). We have concluded that additional time when using the snorkel was lower than the values previously presented in empirical observations (Bentley et al., 2005; Komar et al., 2012; Seifert et al., 2010a), attesting that the new AquaTrainer® ergonomic design facilitates performing the open turn technique presenting an interference of only ~5% when compared to the non-snorkel condition.

The findings of both **Appendix II** and **Chapter 3** were useful to accomplish the following thesis chapters, in which the energetic approach was conducted since:

(i) it was ensured that the use of the snorkel device gives valid ventilatory parameters, not affecting the exertion of the swimmer and, consequently, swimming energetics; (ii) it was possible to use direct oximetry during the entire swimming efforts, which is considered the most valid and precise approach for $\dot{V}O_2$ evaluation (Figueiredo et al., 2011; Rodriguez et al., 2003; Sousa et al., 2014), comparing with the retro-extrapolation method and the Douglas bag technique and; (ii) the direct measurement using the snorkel allowed assessing swimming physiological responses under ecological conditions, avoiding non-specific circumstances (e.g. flume swimming) that could induce some mechanical constraints (Espinosa et al., 2015; Thompson et al., 2004).

Considering the above-mentioned, the physiological response when swimming at moderate intensity was analysed, by assessing (using a specific individual approach) swimmers AnT , considered as an indicator of aerobic capacity swimming performance (Fernandes et al., 2010; Olbrecht, 2000; Smith et al., 2002). Evaluating both AnT_{Met} and AnT_{Vent} (**Chapter 4**), we observed that they occurred at a high $\% \dot{V}O_{2max}$ (Reis et al., 2012; Roels et al., 2005), suggesting that sustaining a high fractional utilization of the $\dot{V}O_{2max}$ can be determinant for good moderate intensity swimming performances. In addition, the similarities between swimming AnT_{Met} and AnT_{Vent} for velocity, $[La^-]$ and HR supported the hypothesis that AnT_{Vent} is directly proportional to AnT_{Met} (Anderson and Rhodes, 1991; Wasserman et al., 1973), and confirmed that the average $[La^-]$ values (e.g. 4 mmol.l⁻¹; Mader et al., 1978), often used to AnT detection, do not represent the individual AnT , particularly in high-level swimmers.

Following the AnT characterisation, it was our purpose to combine the analysis of the moderate front crawl swimming intensity with data obtained at the severe exercise domain, i.e. at $v\dot{V}O_{2max}$. In **Chapter 5**, the energetic approach applied previously in **Chapter 4** was linked to 3D biomechanical analysis, adding new insights to previous 2D biomechanical methodology applied in **Chapter 2**. Results suggested that SF, SL, η_P , IdC and \dot{E} were not determinants of front crawl performance at both moderate and severe front crawl swimming

intensities, once these parameters were unable to detect variations within high-level swimmers' performance. Moreover, no statistical relevant association was found between P_D and front crawl moderate intensity exertion, but, in opposition, a relationship between this parameter and severe intensity domain was observed, according with the literature (Hawley et al., 1992; Pessôa Filho et al., 2014).

The above referred fact could be justified by the observation that, as swimming intensity decreases, the capability of the upper limbs to generate maximum mechanical power for propulsion may be relatively less important than the ability to sustain a high level of aerobic capacity and economy, explaining: (i) the gradual decrease in association magnitude between power and velocity with the decrease in swimming intensity (**Chapters 5 and 8**) and; (ii) from a physiological point of view, the association between moderate and severe intensities, indicating that aerobic capacity is, at a certain point, a necessary component for success when performing at aerobic power velocities (and vice-versa, **Chapter 4**). Moreover, performance efficiency was associated with the severe intensity front crawl velocity, suggesting that a combination of high P_D outputs for the less metabolic input could be considered as a performance determinant at this swimming intensity.

The previously referred swimming intensities are frequently used in training programs to induce biological adaptations necessary for competition. As the majority of swimming events, lasting from 20 s to 2 min, are performed at an extreme exercise intensity, performance seems to be compromised as a consequence of power reduction (as observed later in **Chapter 8**), probably inducing changes on biomechanical parameters (Toussaint et al., 2006). Since propulsion in front crawl depends essentially on upper limbs motion (Deschodt et al., 1999), being particularly linked to the hands parameters (Berger et al., 1995), understanding how fatigue affects upper limb kinematics throughout extreme intensity exercise is of considerable interest to optimise swimming performance. To analyse this issue, an extreme front crawl intensity effort was

monitored (**Chapter 6**), for the first time, using an innovative 3D dual-media automatic tracking system, attempting to obtain a more sensitive analysis to detect minor changes in upper limbs kinematics during the different stages of maximal swimming performance.

As when using this new optoelectronic system, retro-reflective spheres are fixed to the swimmer's body to track his/her movement (Magalhães et al., 2013), following the same line of **Chapter 3**, we analysed the additional drag effect when swimming with these markers. The pilot study (outputs presented during the oral presentation of XII International Symposium on Biomechanics and Medicine in Swimming) revealed that active drag increased when a considerable amount of markers was used, as observed before for passive drag during gliding (Kjendlie and Olstad, 2012). This led us to the attempt of creating an optimal marker setup with as few markers as possible (reducing the drag effect), but simultaneously, enabling a swimmers' body 3D reconstruction.

Data described in the previous paragraph (**Chapter 6**) revealed that fatigue led to a velocity declined due to a SF decrease (as observed later in **Chapter 8**), which probably reduced the swimmers' capacity to apply the same level of propulsive force, since this parameter is essential for force production (as demonstrated herein - **Chapter 2**). Moreover, swimmers tended to adapt their IdC, by diminishing the lag time between propulsive phases, a fact that should be justified by the development of fatigue (Alberty et al., 2008; Alberty et al., 2005; Figueiredo et al., 2013b; Seifert et al., 2005). These results are supported by the decrease in hand velocity, reflecting more time spent during the propulsive phase (higher IdC) rather than greater force generation, in line with the SL decreased.

As previously referred, the better understanding of swimmers metabolic profile is fundamental for designing appropriate training programs and to improve performance (Fernandes et al., 2012; Pyne and Sharp, 2014; Sousa et al., 2014). Results described in **Chapter 7** revealed an instantaneous and sudden

increase of the $\dot{V}O_2$ at the beginning of the exercise that continued to rise until the end of the bout, underlining the contribution of the aerobic energy pathway even at extreme front crawl intensities. In fact, at this intensity domain, the three energy pathways accounted for ~43, 33 and 24% of aerobic, anaerobic lactic and alactic energy contribution (respectively), revealing that, even at swimming intensities higher than those corresponding to $\dot{V}O_{2max}$, both aerobic and anaerobic (lactic and alactic) regimens should be developed to improve final performance.

In addition, considering that $\dot{V}O_2$ kinetics, energy expenditure and, consequently, C, depends on the amount of muscle mass involved in the exercise (Koga et al., 1996; Ogita et al., 2003; Sousa et al., 2015), we complemented our study by monitoring swimmers performing only with the upper body. It was observed that, despite the inferior performance values, the absence of lower limbs action led to a slower $\dot{V}O_2$ kinetics, induced lower aerobic and anaerobic (lactic and alactic) energy demand and, consequently, inferior C. These findings revealed that the lower limbs action could play an important role in the amount of energy liberated and suggest that they have a significant contribution to swimming performance, probably due to propulsion intensification and wave drag reduction (Gourgoulis et al., 2014; Toussaint, 2011).

To complement the findings observed in **Chapters 6 and 7**, and extending the biophysical approach to the extreme domain, we have compared groups of swimmers of different performance levels to analyse how they organize their biophysical performance determinants during the extreme intensity front crawl swimming (**Chapter 8**). It should be stated that to enable power assessment during the effort, the MAD-system apparatus was modified (comparing to the methodology used in **Chapters 2 and 4**) to enable measurements in both directions, so swimmers could swim consecutive laps while recording push off forces.

Results showed that despite most of the studied factors (stroking parameters, P_o , η_P and C) presented the same profile, the higher velocity along the effort of the faster swimmers was attributed to a greater capacity to generate power, corroborating the importance of this parameter in swimming performance (in line with findings for lower swimming intensities - **Chapter 5**). Considering that power is dependent on work per stroke times SF, this could justify the ability of faster swimmers to perform with superior SF, underlining the consequence of this parameter in force generation (**Chapter 2**) and, necessarily, power production (Toussaint et al., 2006; Vorontsov and Binevsky, 2003). Moreover, a high swimming velocity along the extreme domain required a different coordinative solution that could be interpreted as an effective way to deal with fatigue (**Chapter 6**) and to compensate the reduction in power generating ability (Alberty et al., 2005). In fact, a higher coordination pattern variability can be interpreted as a functional property that help swimmers to adapt the movement behaviours according to the swimming performance constraints (Davids et al., 2008; Glazier et al., 2006; Seifert et al., 2014).

Chapter 10 Conclusions

Based on the findings obtained in the experimental moments described in this Thesis, it is pertinent to stress out the following conclusions:

- (i) Considering all range of swimming intensities, a higher front crawl force production required increases in SF and, consequently, superior swimming velocity. This necessarily led to a coordinative adaptation that enabled continuity of the propulsive phases and, consequently IVV decreases.
- (ii) Understanding that the metabolic energy necessary to overcome drag was not affected by the use of a breathing snorkel, front crawl ventilatory and metabolic AnTs were found to be directly associated, corresponding to high $\% \dot{V}O_{2\max}$ values. Moreover, performance at this swimming moderate intensity domain was not statistically explained by the general stroking parameters, η_P , P_D , IdC , \dot{E} , and η_D , but was directly related to $v\dot{V}O_{2\max}$.
- (iii) Both moderate and severe swimming intensities were achieved by distinct intra-individual arrangements of SF, SL, η_P , P_D , IdC , \dot{E} , and η_D . However, and contrarily to the moderate domain, front crawl performance at severe intensity was well associated to P_D and η_D .
- (iv) Fatigue developed at extreme front crawl intensity, provoking changes in swimming technique and, despite the short duration of the effort, both aerobic and anaerobic (lactic and alactic) pathways presented relevant contributions. During this swimming intensity, SF, SL, power, η_P and C profiles seemed not to be performance discriminative, but higher velocities were attributed to superior power, η_P and SF, leading to a higher IdC .

In summary, our findings revealed that each front crawl intensity domain presupposes a specific bioenergetic behavior with consequent distinct

biomechanical implications. Hence, these biophysical particularities of each swimming intensity should be considered during research and training evaluation and control as a way to improve performance.

Chapter 11 Suggestions for Future Research

This thesis considered a biophysical approach to understand the physiological and biomechanical aspects of front crawl locomotion along a large spectrum of intensities. Based on our main findings, it would be important to continue researching in this field of work, particularly by following these ideas:

- (i) Extend the biophysical analysis to other forms of swimming locomotion (especially simultaneous techniques);
- (ii) Combine the analysis of the assessed factors (biomechanical, energetic and coordinative) with muscular parameters;
- (iii) Deepen the coordination analysis based on relationship between spatial and temporal movement characteristics;
- (iv) Analyse the respiratory snorkel effect in eventual front crawl kinematical changes;
- (v) Evaluate the effect of different lower limbs action frequencies on the front crawl locomotion biophysical determinants;
- (vi) Development of a system that allow measuring swimming power with a higher ecological meaning;
- (vii) Analyse power production combining the influence of upper and the lower limbs;
- (viii) Investigate the effect of a wide range of distinct level swimmers and gender on the front crawl locomotion biophysical determinants;
- (ix) Analyse the influence of training in the interplay among the studied factors.

Appendix I

Kinematics of the hip and body center of mass in front crawl.

Ricardo J. Fernandes^{1,2}, João Ribeiro^{1,2}, Pedro Figueiredo^{1,2}, Ludovic Seifert³,
João P. Vilas-Boas^{1,2}

¹ Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport,
University of Porto, Porto, Portugal

² Porto Biomechanics Laboratory, University of Porto, Porto, Portugal

³ University of Rouen, Faculty of Sports Sciences, Rouen, France

Published on Journal of Human Kinetics (2012), 33, 15-23.

Abstract

The kinematic profiles of the hip and center of mass in front crawl swimming were compared to quantify the error of using a fixed body point to assess intracyclic velocity variations at moderate intensity exercise. The practical goal was to provide a useful tool, easy and fast to assess, and to use as feedback, for assessing swimming efficiency. Sixteen swimmers performed an intermittent incremental protocol that allowed assessing the individual anaerobic threshold velocity. One complete stroke cycle was analysed at the step intensity corresponding to each swimmer's anaerobic threshold. Sixteen swimmers were videotaped in the sagittal plane using a double camera set-up for two-dimensional kinematical analyses. The hip and the center of mass presented similar mean velocity and displacement values, being highly related for both parameters; however, the hip reflects the center of mass forward velocity and horizontal displacement with 7.54% and 3.24% associated error, respectively. Differences between hip and center of mass were observed for intracyclic velocity variations (0.19 ± 0.05 and 0.25 ± 0.08 , respectively, for a $p < 0.001$), and the negative mean error value found (-0.06) evidenced a tendency of the hip to overestimate the center of mass velocity variation. It is possible to conclude that the hips forward movements might provide a good estimate of the swimmer's horizontal velocity and displacement that is relevant for diagnostic purposes, especially to assess swimming efficiency through the intracyclic velocity variations; nevertheless, the hip point error magnitude should be taken into consideration in data interpretation.

Key words: Biomechanics, displacement, velocity, validity, applicability

Introduction

Evaluation of swimmers is an essential tool for increasing the efficiency of the training processes and to predict performance (Smith et al., 2002). From the complex group of factors influencing swimming performance, the biomechanical parameters seem fundamental. Recently, Barbosa et al. (2010) evidenced the importance of the swimmer's energetic profile and this one from the biomechanical behaviour. In fact, the importance of improving technique to enhance swimming performance is a topic of great interest for coaches and researchers, being observed that 40% of the 662 papers published in the *Biomechanics and Medicine in Swimming* books (a series of international symposia organized every four years since 1970) had a biomechanical approach (Vilas-Boas et al., 2010).

Studies focusing on swimming biomechanics usually include a kinematic, kinetic, electromyographic or coordinative approach (Barbosa et al., 2008; Schnitzler et al., 2010), but, due to its complexity, swimming technique has been frequently characterized using a simple analysis of the stroking parameters (velocity, stroke rate and stroke length). Its assessment has been carried out since the 1970s (Psycharakis and Sanders, 2009), with long tradition in the technical and scientific swimming community once swimmer's velocity may be explained by the product of frequency and distance per stroke. However, the increasing recognition of its limitations has led to the development of biomechanical equipment and analytical methods, and to a more frequent quantification of other kinematic parameters related to swimming performance (Holmér, 1979; Alberty et al., 2005).

One well-known parameter for the analysis of technical proficiency (Holmér, 1979; Craig et al., 2006; Tella et al., 2008; Seifert et al., 2010), swimming efficiency (Alberty et al., 2005), motor coordination (Schnitzler et al., 2010), and comparison between swimming intensities (Barbosa et al., 2008) and techniques (Maglischo et al., 1987; Craig et al., 2006) has been the intracyclic

velocity variations (IVV). IVV represents the accelerations and decelerations of a swimmer's fixed body point (or body center of mass, CM) within a stroke cycle. Two methods are frequently used for its assessment: (i) the velocity of a fixed point, mostly the hip, using mechanical or image-based methods (Maglischo et al., 1987; Craig et al., 2006; Schnitzler et al., 2010); and (ii) the 2D and 3D reconstruction of the CM motion through digitizing procedures (Maglischo et al., 1987; Barbosa et al., 2008; Psycharakis et al., 2010).

The assessment of the hip's IVV using mechanical procedures takes multiple cycles into consideration, being more training relevant once results and outputs are immediate. This procedure is also very simple and less time consuming (Vilas-Boas et al., 2010) and seems more adequate for practical purposes (Schnitzler et al., 2010). Mechanical assessment of IVV may be performed using velocimetry (Costill et al., 1987; Craig et al., 2006; Schnitzler et al., 2010) and accelerometry (Holmér, 1979; Tella et al., 2008), but, when velocimetry is used only a single swimming pool length can be analysed (due to cable impairments), and its validity has been questioned (Psycharakis and Sanders, 2009). If accelerometers are used, this problem is solved, but the outputs interpretation is not so intuitive, requiring time integration to obtain velocity to time functions; in fact, it was already evidenced that the trunk rotations and inertial effects might affect hip motion when no propulsion or resistance is generated (Psycharakis and Sanders, 2009). The digitizing methods, if validated previously, can also be used to determine the IVV of the hip; this analysis has been done mainly in the horizontal axis of motion (Maglischo et al., 1987; Seifert et al., 2010), once 3D assessment is affected by some errors due to the reconstruction procedure (Figueiredo et al., 2009). The CM reconstruction method seems to be more valid (Barbosa et al., 2003; Psycharakis and Sanders, 2009; Psycharakis et al., 2010), but it is very time-consuming (Maglischo et al., 1987), dependent of the precision of the anthropometric biomechanical model used to calculate the inter-limb inertial effects (Schnitzler et al., 2010), and incurs in significant errors from digitizing procedures, distortion and underwater video techniques (Barbosa et al., 2008; Figueiredo et al., 2009);

in addition, as only one arm cycle is usually analysed, the inter-cycles variability is not considered, having lower applicability for technical training purposes.

The aim of this study was to compare the 2D kinematic profiles of the hip and CM, considering displacement and forward velocity, to quantify the error magnitude of using a fixed body point to assess IVV when swimming front crawl at moderate intensity, which is one of the metabolic zones most stressed in swimming practice (Olbrecht, 2000). It was hypothesized that the 2D estimation of IVV from the hip accurately represents the IVV of the CM, presenting a relevant practical tool to characterize swimmers technique; however, the use of the hip will imply an associated error with a magnitude that should be known and taken into consideration in data interpretation.

Material and Methods

Sixteen long distance swimmers voluntary participated in the present study; the mean \pm SD values regarding their main physical and training background characteristics are: 29.2 ± 10.3 years, body height : 175.1 ± 4.8 cm, arm span: 176.8 ± 5.1 cm, body mass: 67.7 ± 5.7 kg, body fat: 10.9 ± 6.5 kg, lean body mass: 59.1 ± 5.5 kg, and long distance swimming experience: 6.6 ± 5.9 years. All subjects were involved in at least 5 swimming training sessions per week, and participated in regional and national level competitions. The participants provided informed written consent before data collection, which was approved by local ethics committee and performed according to the declaration of Helsinki.

The test session took place in a 25m indoor pool, 1.90 m deep, with a water temperature of 27.5°C , during the preparatory phase of the winter macrocycle. A standardized warm-up of 1000 m of low to moderate aerobic swimming intensity was conducted. Briefly, during the morning (from 9 to 12 am), each subject performed a 7x200 m front crawl individualized intermittent protocol with

increments of 0.05 m/s each step (controlled through a visual pacer - TAR. 1.1, GBK-electronics, Aveiro, Portugal), and 30s rest intervals (Fernandes et al., 2008). Each subject swam alone in one lane, avoiding pacing or drafting effects. Capillary blood samples for blood lactate analysis were collected from the earlobe at rest, during the 30 s rest intervals, at the end of exercise, and during the recovery period (Lactate Pro, Arkay, Inc., Kyoto, Japan), to assess the individual anaerobic threshold through the lactate concentration/velocity curve modelling method (Fernandes et al., 2008; Fernandes et al., 2010). Swimmers were advised not to get involved in high intensity training 24h prior to the experiment, and to maintain their daily nutritional habits.

Swimmers were videotaped in the sagittal plane for 2D kinematical analyses using a double camera set-up, with both cameras (Sony® DCR-HC42E, 1/250 digital shutter, Nagoya, Japan) fixed on a specially designed support for video image recording placed at the lateral wall of the pool and 12.5 m from the start wall (Barbosa et al., 2008). One camera was placed 0.30 m above the water surface and the other was kept 0.30 m underwater (Sony® SPK-HCB waterproof box, Tokyo, Japan) exactly below the surface camera, and at 6.78 m from the plane of movement. Video images were synchronized in real time using a pair of lights visible in the field of each video camera. Subjects were monitored when passing through a specific pre-calibrated space using bi-dimensional rigid calibration structure (6.30 m²) with nine control points.

One complete arm stroke cycle (without breathing) was analysed, being chosen a cycle performed at the middle of the pool (clean swimming) during the 175 m lap of the 200 m step corresponding (or closest) to individual anaerobic threshold velocity. The video images were digitized with the Ariel Performance Analysis System (Ariel Dynamics, San Diego, USA) at a frequency of 50Hz. The CM reconstruction was obtained using the Zatsiorsky and Seluyanov's model, adapted by de Leva (1996), which considered 21 anatomical reference points (vertex, 7th cervical, mandible (mental protuberance), humeral heads, ulnohumeral joints, radiocarpal joints, 3rd dactylions, trochanter major of

femurs, tibiofemoral joints, talocrural joints, calcanei and acropodion), the Direct Linear Transformation algorithm (Abdel-Aziz and Karara, 1971), and a low-pass digital filter of 5 Hz. Considering that the kinematical analysis of the swimming locomotion impose obstacles to data acquisition, particularly by the existence of errors associated to image distortion, digitisation and 2D reconstruction, it seems important to observe its influence on the final results, analysing validity, reliability, and accuracy (Figueiredo et al., 2011). The reliability of the digitizing procedure was assessed by the intraclass correlation coefficient (ICC) of two consecutive digitisations of a randomly selected trial, being 0.99 and 0.69 ($p < 0.001$) for displacement and velocity, respectively.

The displacement and forward velocity of the right hip (trochanter major) and CM in the horizontal axis were selected for analysis. The IVV was calculated through the coefficient of variation of the velocity to time mean values ($CV = SD \times \text{mean}^{-1}$), as proposed by Barbosa et al. (2006) and Schnitzler et al. (2010). The maximum and minimum velocities (v_{\max} and v_{\min} , respectively) were also obtained from the instantaneous velocity data. In addition, the relative v_{\max} and v_{\min} were calculated as a percentage of the stroke cycle mean velocity, and its timing of appearance were computed as a percentage of the stroke cycle duration.

Data were checked for distribution normality with the Shapiro-Wilk test. Considering the CM values as the criterion, the mean error, the root mean square (RMS) error, and the percentage error (RMS error expressed as a percentage of averaged CM values) were calculated for the hip variables. A paired sample *t*-test and the ICC were used to investigate the relationship between the hip and the CM; the mean ICC was obtained by Fisher's *Z'* transformation. All data were analysed using the SPSS version 17.0 (SPSS Inc., Chicago, USA) and the significance level was set at 5%.

Results

Table 1 presents the values regarding the mean \pm SD of the CM and hip for the forward velocity and displacement in the horizontal motion axis, as well as the mean error, the RMS error, the percentage error and the mean ICC between CM and hip. The CM and hip presented similar values both for velocity and displacement. In fact, the ~ 0 values of the mean error indicate that the hip does not under or overestimates the CM velocity values; however, concerning the displacement variable, a slight tendency for a hip underestimation is shown. Conversely, concerning the values of RMS error and percentage of error, the hip reflects with higher error the CM in the velocity than in the displacement variable. Furthermore, high positive correlation coefficient values were found between the hip point and the CM regarding both horizontal swimming velocity and displacement.

Table 1. Mean \pm SD values of velocity and displacement of the centre of mass and hip, and the mean error, root mean square (RMS) error and percentage error. Mean intraclass correlation coefficient (ICC) between hip and centre of mass is also displayed (n=16).

Variable	Centre of mass	Hip	Mean error	RMS error	Percentage error	Mean ICC	Significance (p)
velocity ($\text{m} \times \text{s}^{-1}$)	1.06 \pm 0.26	1.06 \pm 0.32	0.00	0.18	7.54	0.71	p<0.001
displacement (m)	2.16 \pm 0.32	2.16 \pm 0.34	0.06	0.07	3.24	0.99	p<0.001

Complementarily, a typical forward velocity to time profile of the hip and CM (for both right and left arm strokes) is displayed in Figure 1, being observable positive accelerations of the hip and CM during the insweep and upsweep phases of the left arm (coincident with the entry of the right arm), and during the catch of the right arm. The hip and CM negative accelerations occurred during the transition between propulsive phases, and in the downsweep coincident with the recovery of the opposite arm. It is also evidenced that the hip presents higher forward velocity peaks magnitude comparing to the CM.

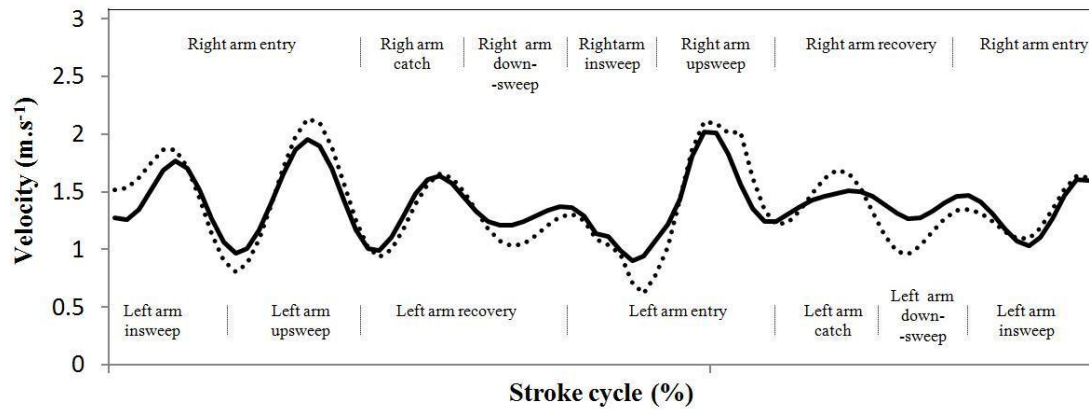


Figure 1. Example of the intracyclic velocity variations of the hip (dashed line) and of the centre of mass (continuous line) for one swimmer.

Table 2 presents the descriptive statistics for the CM and hip velocity related variables, showing also the p value regarding eventual differences between CM and hip. The mean and RMS errors are also displayed, evidencing the validity of the hip values when using the CM values as criterion. Differences between CM and hip were observed for IVV, v_{\max} , v_{\min} , relative v_{\max} , and relative v_{\min} . The negative mean error values found for the IVV, v_{\max} , relative v_{\max} , timing v_{\max} and timing v_{\min} show a tendency of the hip to overestimate the CM values (the positive mean errors illustrate the opposite behavior). The greater RMS values were identified in the timing of appearance of v_{\max} and v_{\min} during the stroke cycle.

Table 2. Mean \pm SD values of the centre of mass and hip velocity related variables (p value is also shown). The mean and RMS errors are also displayed (n=16).

Variable	Centre of mass	Hip	Paired samples t-test (p)	Mean error	RMS error
IVV	0.19 \pm 0.05	0.25 \pm 0.08	< 0.001	-0.06	0.07
v_{\max} (m/s)	1.59 \pm 0.27	1.73 \pm 0.29	0.001	-0.14	0.19
v_{\min} (m/s)	0.57 \pm 0.22	0.46 \pm 0.21	0.003	0.11	0.17
Relative v_{\max} (%)	147.77 \pm 0.18	159.91 \pm 0.17	0.002	-12.14	17.37
Relative v_{\min} (%)	53.03 \pm 0.20	43.22 \pm 0.21	0.003	9.81	14.45
Timing v_{\max} (%)	35.11 \pm 0.26	45.44 \pm 0.26	0.257	-10.33	35.30
Timing v_{\min} (%)	48.17 \pm 0.24	55.51 \pm 0.25	0.171	-7.34	21.15

IVV: intracycle velocity variation, v_{\max} : maximum velocity, v_{\min} : minimum velocity, and RMS: root mean square.

Discussion

The key to success in swimming does not rely on hard training, but purposely and carefully (Olbrecht, 2000), meaning that training should be well planned and monitored (Smith et al., 2002). Knowing that changes of the horizontal velocity during a stroke cycle is a topic increasingly popular among coaches and researchers (Psycharakis and Sanders, 2009; Barbosa et al., 2010; Vilas-Boas et al., 2010), it was aimed to compare the IVV kinematic profiles of the hip and CM in front crawl swimming to quantify the error of using a fixed body point to assess IVV. As IVV is an important indicator of swimming technique (Barbosa et al., 2008), which is a major factor influencing swimming performance (Costill et al., 1987; Smith et al., 2002). The pertinence of the current study is perfectly justified once it has great practical applicability.

The above-referred analysis was conducted at an intensity corresponding to the metabolic individual anaerobic threshold velocity, i.e., at the highest exercise intensity at which a balance between the production and removal of lactate occurs (Olbrecht, 2000). This velocity was selected since it is often used in training, representing the maximum aerobic velocity that swimmers can maintain without accumulation of fatigue (approximately 30min) (Olbrecht, 2000, Fernandes et al., 2010). Previous attempts in observing whether the hip represents accurately the intracycle CM profile in front crawl have been conducted at much higher intensities (Maglischo et al., 1987; Psycharakis and Sanders, 2009), being expected higher IVV values due to the dramatic increase in both propulsive and drag forces (Schnitzler et al., 2010). In fact, Barbosa et al. (2006) found a linear relationship between IVV and energy cost, and, therefore, with velocity, in the front crawl.

In the current study, a 2D kinematical recording was implemented since it requires less digitizing time and has fewer methodological problems. In fact, the 2D approach is conceptually easier to relate to, and can yield acceptable results (Bartlett, 2007), being proper to evaluate numerous samples and to implement

in field studies, particularly in the swimming club; conversely, the 3D analysis is a very time-consuming process that requires complex analytical methods, which makes it difficult for coaches to use on a day-to-day basis (Psycharakis and Sanders, 2009).

CM and hip presented similar mean values for both forward velocity and displacement; this was expected once the CM is located in the hip region, existing high proximity (Costill et al., 1987; Maglischo et al., 1987; Figueiredo et al., 2009). In fact, nonetheless the mean error concerning the hip and CM displacement towards a slight tendency for a hip underestimation, the approximately 0 velocity mean error values indicate that the hip seems not to under or overestimate the CM velocity values; this is in line with the literature, concluding Maglischo et al. (1987) that forward velocity of the hip can be a useful tool for diagnosing problems within stroke cycles. However, the values of RMS error and percentage of error evidence the opposite behaviour: although being of low magnitude, the error is higher regarding forward velocity (7.54%) than the displacement (3.24%). It is accepted that the RMS error should be considered preferably to the mean error, since the hip frequently underestimates or overestimates the CM due to differences in swimmers' technique (negative errors cancelled by the positive ones), and because RMS is considered a conservative estimate of accuracy (Allard et al., 1995).

Furthermore, high and very high positive correlation coefficients were found between the hip and the CM regarding horizontal swimming velocity and displacement, as seen for front crawl (Costill et al., 1987; Maglischo et al., 1987, Figueiredo et al., 2009), backstroke (Maglischo et al., 1987), breaststroke (Costill et al., 1987; Maglischo et al., 1987), and butterfly (Maglischo et al., 1987; Barbosa et al., 2003). Considering each swimmer individually, a positive correlation was observed between the hip and CM values regarding velocity (ranging from 0.50 to 0.83), which is in accordance with Maglischo et al. (1987) on front crawl technique (values between 0.86 and 0.96, with a mean coefficient of 0.87). These data, associated with the obtained high digitize-redigitize

reliability values, evidence that, although there is an associated error that should be taken into account, the hip reflects satisfactorily the CM motion in front crawl when swimming at moderate intensity.

The velocity to time curve obtained for one swimmer for both CM and hip showed similar patterns of positive and negative accelerations as described in the literature (Maglischo et al., 1987; Craig et al., 2006): both CM and hip decelerated during the downsweep phases (that are coincident with the recovery of the opposite arm) and in the transition from one propulsive phase to another, and both body points accelerated during the catch, insweep and upsweep phases. Thus, coaches should incorporate specific training drills aiming to perform faster transitions between propulsive phases, as well as to finish the stroke at maximal arm velocity. It was also evident that swimmers choose a catch-up inter-arm coordination mode that is typical of moderate paces due to a long gliding phase (Schnitzler et al., 2008; Seifert and Chollet, 2009; Seifert et al., 2010); in fact, the existence of a discontinuity between the end of the propulsion of one arm and the beginning of propulsion of the other arm is typical of front crawl swimming at moderate intensities (Seifert and Chollet, 2009; Seifert et al., 2010). So, coaches should not advise swimmers to adopt superposition arm synchronization when implementing aerobic pace training series. Furthermore, it was also evidenced that the hip presents higher and lower forward velocity peaks magnitude compared to CM, as shown by Maglischo et al. (1987) for higher swimming intensities.

Notwithstanding that the forward velocity and displacement of the hip and CM are similar, and the evidence that the IVV determination using the hip is reliable, allows multiple cycles to be evaluated and enables the assessment of fatigue (Holmér, 1979, Maglischo et al., 1987), differences between hip and CM were found for the IVV. Such differences corroborates the literature (Figueiredo et al., 2009), and might be explained by the inter-segmental actions during the front crawl swimming cycle that frequently changes the CM position (Barbosa et al., 2003). In addition, the CM v_{max} and v_{min} values seem to be over and

underestimated (respectively) by the hip values, as previously proposed by Psycharakis and Sanders (2009). In fact, when the arms in front crawl accelerate the body mass, they simultaneously move backwards with respect to a body fix landmark refraining the acceleration of the CM. The same is expected in case of the negative accelerations determined by body drag prevalence: during the drag dominated phases, one arm is recovering (moving forward with respect to a fix body point), reducing the total negative acceleration of the CM comparatively to a body landmark. Meanwhile, the observed differences may be lower than previously found for maximal front crawl swimming (Maglischo et al., 1987; Figueiredo et al., 2009; Psycharakis and Sanders, 2009), because the current study was conducted at moderate intensity that is also characterized by lower positive and negative intracyclic accelerations (Tella et al., 2008). In fact, increases in IVV are associated with the swimmers acceleration capacity that is greater at higher swimming intensities (Schnitzler et al., 2010).

Despite the dissimilarities, the kinematics of the hip and CM are easily explainable. It should be emphasized that errors associated with the CM assessment, particularly concerning images quality, digitizing, calibration, refraction and reconstruction, and inertial models (Vilas-Boas et al., 2010; Figueiredo et al., 2011), may also contribute to the observed differences. In addition, the CM position varies (e.g. with the breathing pattern and with the distribution of body fluids, Bartlett, 2007), being its estimation less accurate when shoulder movement is involved (Plagenhoef, 1976), as it occurs in front crawl swimming. Finally, no differences were observed between the CM and hip concerning the timing of v_{max} and v_{min} , despite the high RMS values, as reported by Psycharakis and Sanders (2009). Furthermore, despite that the calculation of hip velocity based on 2D analysis may increase the possibility of errors, lower and/or similar RMS values were registered for the above-referred velocity variables than those reported using a 3D approach (Psycharakis and Sanders, 2009).

The current results showed that IVV assessed from the hip could be useful to characterize swimming technique, evidencing the combination between propulsive and resistive forces. Our data suggests that, when implementing aerobic conditioning training in swimming, coaches should include drills aiming to accomplish faster transitions between propulsive phases, and to finish the front crawl stroke at maximal arm velocity. It is evidenced that plotting the hip to assess swimmer's forward velocity and displacement is a simple and fast process that enables evaluating multiple cycles and giving quick feedback to swimmers. However, when using the hip as a measure of forward velocity and/or displacement, the associated error (~7 and 3%) should always be taken into consideration.

Acknowledgments

This study was supported by grant: PTDC/DES/101224/2008 (FCOMP-01-0124-FEDER-009577).

Appendix II .

Is the New AquaTrainer® Snorkel valid for $\dot{V}O_2$ Assessment in Swimming?

Carlo Baldari¹, Ricardo J. Fernandes^{2,3}, Marco Meucci¹, João Ribeiro², João P. Vilas-Boas^{2,3}, Laura Guidetti¹

¹ Department of Movement, Human and Health Sciences University of Rome “Foro Italico”, Rome, Italy.

² Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal

³ Porto Biomechanics Laboratory, University of Porto, Porto, Portugal

Published on International Journal of Sports Medicine (2013), 34 (4), 336-344

Abstract

The Cosmed AquaTrainer® snorkel, in connection with the K4b² analyzer, is the most recent instrument used for real time gas analysis during swimming. This study aimed to test if a new AquaTrainer® snorkel with 2 (SV2) or 4 (SV4) valves is comparable to a standard facemask (Mask) being valid for real time gas analysis under controlled laboratory and swimming pool conditions. Nine swimmers performed two swimming and three cycling tests at three different workloads in separate days. Tests were performed in random order, at constant exercise load with direct turbine temperature measurements, breathing with Mask, SV4 and SV2 while cycling, and with SV2 and SV4 while swimming. A high agreement was obtained by Passing–Bablok regression analysis in oxygen consumption, carbon dioxide production, tidal volumes, pulmonary ventilation, expiratory fraction of oxygen and carbon dioxide, and heart rate comparing different conditions both swimming and cycling. Proportional and fixed differences were always rejected (95% CI always contained the value 1 for the slope and the 0 for the intercept). In conclusion, the new SV2 AquaTrainer® snorkel, can be considered a valid device for gas analysis, being comparable to the Mask and the SV4 in cycling, and to the SV4 in swimming.

Key words: Respiratory valves, K4b², oxygen consumption, energetics

Introduction

The analysis of oxygen uptake (VO_2) during exercise is a common practice in sport physiology. Historically, the Douglas bag method was used to analyze gas exchange, collecting exhaled air in impermeable canvas later analyzed as gas fraction (Douglas, 1911). Until the 1990s, the VO_2 during swimming, in flume, with pulley system, or freely swimming in a pool, was assessed directly using a Douglas bag or a mixing chamber analyser (Di Prampero et al., 1974; Holmer, 1974; Vilas-Boas and Santos, 1994) or indirectly using a backward extrapolation method (Lavoie and Montpetit, 1986). At the beginning of the 1990s, the portable Cosmed K2 telemetry gas analyzer (Cosmed K2, Italy) allowed direct gas analysis through the use of a face mask, a flow meter, and an O_2 gas analyzer. The system was considered accurate for cardiopulmonary analysis compared to the Douglas bag method (showing a measurement error less than 2%; Kawakami et al., 1992) and to the conventional stationary gas analyzer (Lucía et al., 1993; Peel and Utsey, 1993). A few years later, the Cosmed K4 was designed, and later upgraded to the K4b² portable telemetry system to obtain BxB measurement (Cosmed K4b², Italy) of cardiopulmonary parameters including both O_2 and CO_2 analysis. They showed a good accuracy at different exercise intensities, thus proved to be a valid measurement for gas exchange (Doyon et al., 2001; Duffield et al., 2004; Hausswirth et al., 1997; McLaughlin et al., 2001). In fact, K4b² was been frequently used in swimming, in connection with a snorkel device, to assess VO_2 on-kinetics in rectangular and graded protocols (Sousa et al., 2011; Reis et al., 2010).

To evaluate energetic cost of swimming, snorkel devices had been used to collect O_2 and CO_2 in swimming pool (Holmer, 1972; Pendergast et al., 1977; Toussaint et al., 1990). Toussaint et al. (1987) firstly validated a snorkel and a valve system, with reduced drag and a dead space of 30 ml, to collect expired air in Douglas bags during swimming. Few years later, Dal Monte et al. (1994) designed a snorkel and valve system in carbon fiber with a frontal single tube improving the hydrodynamics in flume conditions. He reduced the dead space

at 15 ml and connected this apparatus to a miniaturized telemetry system for VO_2 measurements. More recently, Keskinen et al. (2003) upgraded the snorkel of Toussaint et al. (1987) adapting it to the K4b² (Cosmed S.r.l., Rome, Italy) for real time measurements. They claimed it was a valid instrument for breath-by-breath (BxB) analysis being in line with the standard facemask, but reporting a moderate difference (3-7%) in the respiratory and gas exchange values (McLaughlin et al., 2001). Later, Rodriguez et al. (2008) drew similar conclusions testing a smaller and a larger volume snorkel in comparison with the direct turbine connected to a gas exchange simulator. In fact, both devices were considered valid to measure pulmonary BxB gas exchange parameters, but the regression analysis reported a somewhat larger deviation in VO_2 (7%) and VCO_2 (3%). Similar results were obtained by Gayda and colleagues (Gayda et al., 2010) that comparing the snorkel AquaTrainer[®] and K4b² system to the standard facemask through a cycling test, observed a difference in VO_2 of ~15%. Therefore, they categorized the AquaTrainer[®] system as not acceptable for field-testing when compared to the standard facemask; this study rose a debate about the validity of the instrumentation, pointing out the necessity to take into account some technical notes when the AquaTrainer[®] device is used in conjunction with the K4b² (Brugnoli, 2010; Gayda et al., 2011).

To find a possible explanation to the deviations in VO_2 reported by previous studies (Gayda et al., 2010; Keskinen et al., 2003; Rodriguez et al., 2008), a detailed study protocol, including expired air temperature detections, was used. Moreover, in order to reduce gas mixtures and reduce resistances and air turbulence while breathing, the newly Cosmed AquaTrainer[®] system present some upgrades as the reduced dead space, two flexible but not stretchable tubes with larger size and shorter length, larger size Hans-Rudolf valves and a smooth internal valves assembly surface in comparison with the snorkel of Keskinen et al. (2003). Moreover, to improve comfort during swimming, structural modifications including a soft and oval mouthpiece, a flexible head connection, and flexible but underwater stable tubes were used.

Our study had two main aims a) to establish if the newly Cosmed AquaTrainer® system is proper for VO_2 assessment, comparing it to the commonly used standard facemask; b) to compare the standard two valves AquaTrainer® with a four valves configuration and detect the agreement between systems.

Material and methods

Nine active swimmers (4 male and 5 female, age 24.3 ± 6.2 and 25.2 ± 5.3 years, respectively) voluntary participated in this study. All the subjects were healthy athletes regularly exercising at least 3 times a week in the last year and occasionally or regularly competing in regional events. Anthropometric measures (height and body mass) of male and female were 180 ± 2 and 165 ± 4 cm and 72.8 ± 2.5 and 57.8 ± 3.6 kg, respectively. Written informed consent was obtained from all subjects and the protocol was approved by Local Ethic Committee. This study has been performed in accordance with the ethical standards of the International Journal of Sports Medicine (Harriss and Atkinson, 2011). All subjects had previous experience of VO_2 measurements in swimming using different types of snorkel, and were encouraged to subjectively compare the comfort afforded them by the new prototype when compared to past models. After swimming with the new AquaTrainer® snorkel subjects were individually interviewed to ask if there were any differences in comfort in comparison with the models previously experimented, and then invited to describe eventual perceived differences.

Study design

On different days, subjects underwent two exercise protocols: one in a 25 m swimming pool (1.90 m deep, water temperature of 27°C , constant ambient temperature of 28°C , 50% of humidity, and ventilated environment), and the other on a cycle ergometer (Monark 928E testing Ergometer). The swimming and cycling protocols counted two and three exercise sessions, respectively, separated by 24-48 h. Each session was composed of three constant exercise

bouts: the first two performed at low or moderate intensity (below or around the lactate threshold) with a brief interval in between, and the third, after 15 min of complete recovery, was performed at high intensity (above the lactate threshold) (Figure 1).

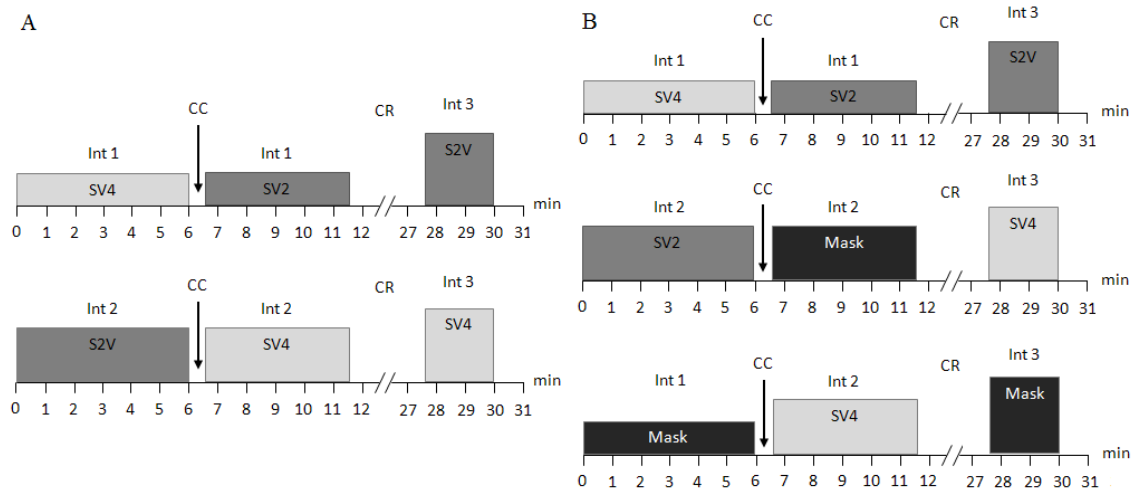


Figure 1. Exercise protocol with (A) cycle ergometer and (B) swimming snorkel AquaTrainer performed at three different intensities (Int 1: low intensity, Int 2: moderate intensity, Int 3: high intensity). CC, Change Condition; CR, Complete Recovery.

Each exercise bout was performed in a different condition: with the AquaTrainer® prototype with 2 (SV2) and 4 valves (SV4), and with a standard mask (Mask). During the swimming test subjects performed two exercise sessions with two conditions (SV2 and SV4) (Figure 1A), during cycling three sessions and all three conditions were used (Figure 1B). Conditions were randomly assigned between, and within, each exercise session. Subjects were asked to abstain from smoking and consuming alcohol or caffeine, 48 h prior to exercise testing, and to avoid strenuous exercise 12 h prior to exercise testing.

Exercise tests

Before the first test session, subjects were familiarized with the instruments and underwent a test to establish the swimming velocity at the individual lactate threshold using a single-session 7×200 m (30s rest interval) intermittent incremental protocol (Fernandes et al., 2011). To identify the high exercise intensity, the velocity of the 7×200 m step corresponding to maximal oxygen

consumption was used to test the subjects on a 250 m bout. The low, moderate and high intensities of the cycling test were established extrapolating from the modified Astrand-Ryhming nomogram (Armstrong et al., 2006) the power value (in W) corresponding to the VO_2 of each individual exercise intensity in swimming. During the swim tests, subjects exercised using front crawl technique at a constant velocity between 0.7 and 1.0 m/s for the low, 0.8 and 1.1 m/s for the moderate and 0.95, and 1.33 m/s for the high intensity. During the cycle tests, subjects pedaled at a constant frequency of 60 rpm at 50-100, 100-150 and 175-275 W for the low, moderate and high intensities, respectively. To keep constant the exercise intensity, subjects used a light pacing device (TAR. 1.1, GBK-electronics, Aveiro, Portugal) when swimming and the cycle ergometer display when cycling. The exercise intensity during both swimming and cycling tests was further controlled between and within exercise bouts through blood lactate (Lactate Pro, Arkay, Inc, Kyoto, Japan), VO_2 and HR, respectively.

Gas analyzer, calibration and setting

To obtain a valid and accurate data, standardized turbine (3 L), gas (ambient air with 20.94% O_2 and 0.03% CO_2 , and reference gas mixture with 16.00% O_2 and 5.00% CO_2) and delay calibration procedures were performed before each test according to the manufacturer's recommendations (see "K4b² user manual" Cosmed Ltd., 2011: 44-47), and a dry gas sampling line was used for each test. Atmospheric pressure and ambient temperature were measured by the K4b² portable unit and relative humidity was measured and manually reported to the K4b² before each test. At the end of each exercise bout, temperature at the turbine was measured with an infrared thermometer (infrared thermometer, Kramer, Med.Ico). Temperature was sampled three times and averaged to obtain the final value. Respiratory gas exchange was detected BxB with a portable telemetric gas analyzer (Cosmed K4b², Cosmed, Italy) in both swimming and cycling conditions. HR was detected by a polar heart rate belt, and transmitted to the K4b² portable unit. Expired gas were sampled at the turbine through a semipermeable Nafion sampling line (0.75 m in length), and

analyzed into the Cosmed K4b² portable unit through O₂ and CO₂ analyzers. All data were also transmitted by telemetry from the Cosmed K4b² portable unit to a personal computer and controlled in real time.

AquaTrainer[®] system

The new AquaTrainer[®] prototype (Figure 2) reported many structural upgrades in order to improve accuracy of measurements and comfort in usage. This device was developed with the cooperation of the fast prototyping unit of the Engineering Faculty of the University of Porto (INEGI), Portugal.

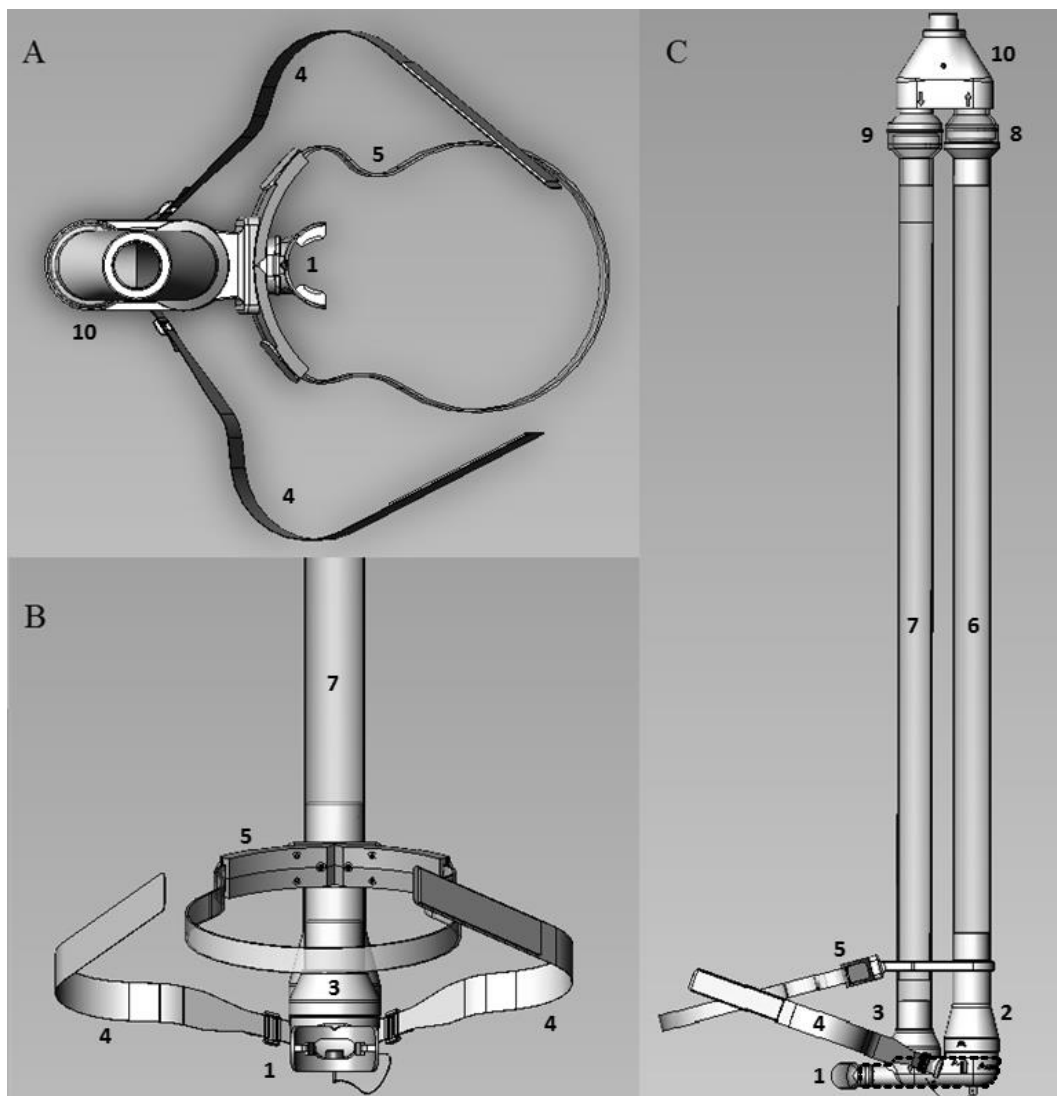


Figure 2. Upper (A), frontal (B) and lateral (C) (dead space delimited in dotted line) representation of the AquaTrainer[®] prototype system. 1 = Mouthpiece, 2 = lower expiration valve, 3 = lower inspiration valve, 4 = neck connection, 5 = head connection, 6 = expiration

tube, 7 = inspiration tube, 8 = upper expiration valve, 9 = upper inspiration valve, 10 = connection tubes unit.

Differences between this prototype and the model of Keskinen et al. (2003) include upgrades such as: 1) more flexible but not stretchable canalization tubes (constant distance and volume between the mouthpiece and the turbine); 2) smoother inner surfaces of the inspiratory and expiratory tubes (intending to improve internal flow dynamics); 3) shorter expiratory and inspiratory tubes; 4) a system to balance both tubes in a underwater stable position was included; 5) the dead space at the valves assembly, as considered by other authors as the space between the mouthpiece and the lower inspiratory and expiratory valves (Dal Monte et al., 1994; Rodriguez et al., 2008; Toussaint et al., 1987), was reduced to 11.3 ml; 6) the mouthpiece shape is oval instead of circular, to better adjust to the conformation of the mouth, 7) the valves (Hans-Rudolf) are of different configuration and dimension (35 mm of diameter compared to the previous 28 mm); 8) shorter canalization tubes (from 128 cm to 86 cm); 9) the head connection support is softer, flexible and better anatomically oriented, and 10) a system to drain the internal fluids accumulated into the valves assembly during tests was included. The AquaTrainer® prototype has been designed to add or remove the upper valves to test the snorkel device with two and four valves. The SV2 model presents only the inspiration and expiration lower two valves while the SV4 model presents also the upper inspiration and expiration once to prevent mixtures between inspiratory, expiratory and ambient air. Different from the old AquaTrainer® (Gayda et al., 2010), the new model presents some upgrades: a) the tubes of canalization are conveyed in a unique connector attached to the turbine so that the K4b² software automatically discerns the in/ex by the shift of the turbine spin; b) in order to reduce the internal resistances, the expiratory tube is shorter (from 128 cm to 86 cm) and the inspiratory tube is longer (from 128 cm to 86 cm), being now of the same length, and both were enlarged (from 28 mm to 35 mm) counting a volume of 847 ml from the mouthpiece to the turbine; c) it uses an open support instead of a closed briefcase to contain the K4b² portable unit (see “Tips and suggestion on how to use AQUATRAINER” Cosmed Ltd., 2005: 9-11), which prevents from

overheating and samplings of stale air in case of auto-calibration; d) the HR receiver is now waterproof and positioned at the mouthpiece level attached to the tubes of canalization being into the HR detection area, reducing the risk of signal interferences; e) the internal surface of the snorkel valves assembly (which includes the mouthpiece and the first set of valves) is more smooth in order to reduce turbulence of the air while breathing (data not reported in this paper); f) to improve the comfort in usage, the mouthpiece shape is oval instead of circular, to better adjust to the conformation of the mouth, and the head connection support is more soft and flexible.

Treatment of data

BxB data of each test were reduced by excluding errant breaths caused by swallowing, coughing or signal interruptions once they were considered too different from the real kinetics. Values greater and lower than 4 standard deviations from the local mean were omitted (Özyener et al., 2001). The last 3 min of each step were smoothed at 6 breaths, and then averaged at 30 s for low and moderate exercise intensities, and at 15 s for the high intensity, using the averaging function of the Cosmed analysis software. The temperature of the expired air detected at the snorkel turbine was reported a posteriori to the Cosmed software to adjust volumes. Different from the standard procedure, which require the use of the ambient temperature, we used the temperature of the expired gas instead of the ambient air.

Statistical analysis

Agreement between different conditions in swimming (SV2 vs SV4) and cycling (SV2 vs Mask, SV4 vs Mask, SV2 vs SV4) was evaluated for $\dot{V}O_2$, carbon dioxide production ($\dot{V}CO_2$), tidal volumes (V_T), pulmonary ventilation (\dot{V}_E), expiratory fraction of oxygen (F_{EO_2}) and carbon dioxide (F_{ECO_2}), and HR by Passing-Bablok regression analysis (MedCalc Software, ver. 11.6, Mariakerke, Belgium). The agreement between couples of conditions within each test was performed with Bland-Altman analysis using an ancillary software. Pearson's coefficient of determination (R^2) was computed. For the Passing-Bablok

regression equations, regression parameters (slope and intercept), and 95% confidence intervals (95% CI), were calculated to determine the degree of association between two methods. Accuracy was quantified as the mean of the differences (bias) between two conditions, one of them used as reference or criterion condition. A 95% CI that include the 0 for the intercept and the 1 for the slope allow to reject the hypothesis of fixed and proportional differences respectively.

Results

The R^2 values, Passing-Bablok regression equation parameters (slope and intercept), and the mean difference of the cardiorespiratory parameters measured with the new snorkel AquaTrainer® with 2 and 4 valves in swimming (SV2 vs SV4), and also with the standard mask in cycling (SV2 vs SV4, SV2 vs Mask, SV4 vs Mask), are reported in Table 1.

Table 1. Agreement values obtained by the snorkel AquaTrainer® with 2 (SV2) and 4 (SV4) valves and the standard mask (Mask) in swimming and cycling assessed by Passing-Bablok regression analysis. Pearson's determinant coefficient (R^2), mean difference, slope and intercept of the differences are reported.

SV4 vs SV2 (N = 27, Swimming)				
Parameters	R^2	Slope	Intercept	Mean difference
VO ₂ (mL·min ⁻¹ , STPD)	0.991	0.995 (0.950 to 1.040)	-12.705 (-119.201 to 81.186)	-18.7 (-180.0 to 143.5)
VCO ₂ (mL·min ⁻¹ , STPD)	0.996	0.992 (0.965 to 1.022)	8.227 (-53.300 to 61.519)	-13.9 (-128.8 to 101.1)
V _E (L·min ⁻¹ , BTPS)	0.992	0.992 (0.957 to 1.023)	-0.514 (-2.382 to 1.817)	-0.47 (-4.49 to 3.55)
V _T (L, BTPS)	0.920	1.068 (0.911 to 1.230)	-0.122 (-0.443 to 0.182)	0.01 (-0.25 to 0.26)
F _E O ₂ (%)	0.826	0.940 (0.783 to 1.155)	0.984 (-2.515 to 3.564)	-0.02 (-0.49 to 0.44)
F _{EC} O ₂ (%)	0.894	1.000 (0.844 to 1.258)	0.020 (-0.996 to 0.641)	0.01 (-0.28 to 0.31)
HR (beats·min ⁻¹)	0.991	1.000 (0.941 to 1.015)	0.500 (-2.015 to 8.765)	0.19 (-4.49 to 4.86)
Mask vs SV2 (N = 27, Cycling)				
Parameters	R^2	Slope	Intercept	Mean difference
VO ₂ (mL·min ⁻¹ , STPD)	0.994	1.001 (0.967 to 1.043)	-6.126 (-90.863 to 56.145)	-2.8 (-124.9 to 119.3)
VCO ₂ (mL·min ⁻¹ , STPD)	0.996	1.012 (0.978 to 1.044)	-42.292 (-104.030 to 23.499)	-11.3 (-126.3 to 103.7)
V _E (L·min ⁻¹ , BTPS)	0.992	1.008 (0.960 to 1.044)	-0.252 (-2.283 to 2.098)	0.14 (-3.68 to 3.96)

V_T (L, BTPS)	0.947	1.000 (0.864 to 1.132)	0.009 (-0.246 to 0.288)	0.01 (-0.20 to 0.22)
F_{EO_2} (%)	0.837	0.950 (0.785 to 1.146)	0.884 (-2.404 to 3.626)	0.04 (-0.28 to 0.37)
F_{ECO_2} (%)	0.869	0.922 (0.774 to 1.132)	0.259 (-0.613 to 0.843)	-0.06 (-0.31 to 0.18)
HR (beats·min ⁻¹)	0.990	1.000 (0.942 to 1.024)	-1.000 (-3.857 to 9.154)	0.03 (-5.68 to 5.74)
Mask vs SV4 (N = 27, Cycling)				
Parameters	R ²	Slope	Intercept	Mean difference
VO_2 (mL·min ⁻¹ , STPD)	0.998	1.006 (0.987 to 1.026)	-1.628 (-44.755 to 27.139)	0.9 (-66.0 to 67.7)
VCO_2 (mL·min ⁻¹ , STPD)	0.998	1.020 (0.995 to 1.043)	-27.075 (-62.093 to 7.944)	-5.1 (-88.8 to 78.5)
V_E (L·min ⁻¹ , BTPS)	0.996	1.017 (0.987 to 1.044)	-1.239 (-2.952 to 0.828)	-0.10 (-2.98 to 2.77)
V_T (L, BTPS)	0.914	1.009 (0.850 to 1.204)	-0.025 (-0.367 to 0.327)	0.01 (-0.26 to 0.28)
F_{EO_2} (%)	0.839	0.995 (0.822 to 1.220)	0.059 (-3.702 to 2.962)	-0.04 (-0.37 to 0.29)
F_{ECO_2} (%)	0.904	0.958 (0.836 to 1.141)	0.177 (-0.622 to 0.680)	-0.01 (-0.22 to 0.19)
HR (beats·min ⁻¹)	0.990	1.000 (0.944 to 1.019)	-1.000 (-3.111 to 7.889)	-0.22 (-5.83 to 5.38)
SV4 vs SV2 (N = 27, Cycling)				
Parameters	R ²	Slope	Intercept	Mean difference
VO_2 (mL·min ⁻¹ , STPD)	0.997	1.000 (0.972 to 1.028)	-5.000 (-63.961 to 64.083)	-5.7 (-94.4 to 83.0)
VCO_2 (mL·min ⁻¹ , STPD)	0.998	0.994 (0.970 to 1.017)	-2.130 (-38.621 to 59.186)	-6.1 (-89.2 to 77.0)
V_E (L·min ⁻¹ , BTPS)	0.997	0.988 (0.956 to 1.018)	1.062 (-0.348 to 2.654)	0.24 (-2.32 to 2.81)
V_T (L, BTPS)	0.938	0.949 (0.818 to 1.100)	0.097 (-0.191 to 0.317)	0.00 (-0.24 to 0.23)
F_{EO_2} (%)	0.856	0.996 (0.829 to 1.156)	0.129 (-2.552 to 2.926)	0.09 (-0.22 to 0.39)
F_{ECO_2} (%)	0.836	1.000 (0.808 to 1.196)	-0.060 (-0.856 to 0.729)	-0.05 (-0.32 to 0.22)
HR (beats·min ⁻¹)	0.987	1.000 (0.941 to 1.042)	1.000 (-6.375 to 9.000)	0.22 (-6.13 to 6.57)

VO_2 , oxygen uptake; VCO_2 , carbon dioxide production; V_E , pulmonary ventilation; V_T , tidal volume, F_{EO_2} , expiratory fraction of oxygen; F_{ECO_2} , carbon dioxide; HR, heart rate.

Cardiorespiratory values obtained with the two and four valves AquaTrainer® and with the standard mask were highly correlated in all conditions with an $R^2 > 0.99$ in VO_2 , VCO_2 , and V_E parameters. Passing-Bablok regression analysis (Passing and Bablok, 1983) of all parameters (VO_2 , VCO_2 , V_E , V_T , F_{EO_2} , F_{ECO_2} , and HR), comparing the standard mask with the 2 and 4 valves snorkel conditions in cycling and the 2 and the 4 valves in both swimming and cycling, reported slope and intercept values that include the 1 and the 0 respectively.

The Passing-Bablok regression analysis and the Bland-Altman (Bland and Altman, 1986) plots of the averaged VO_2 , VCO_2 and V_E values obtained during swimming and cycling tests between the standard mask, the 2 and 4 valves were graphically shown in Figure 3, Figure 4 and Figure 5 respectively.

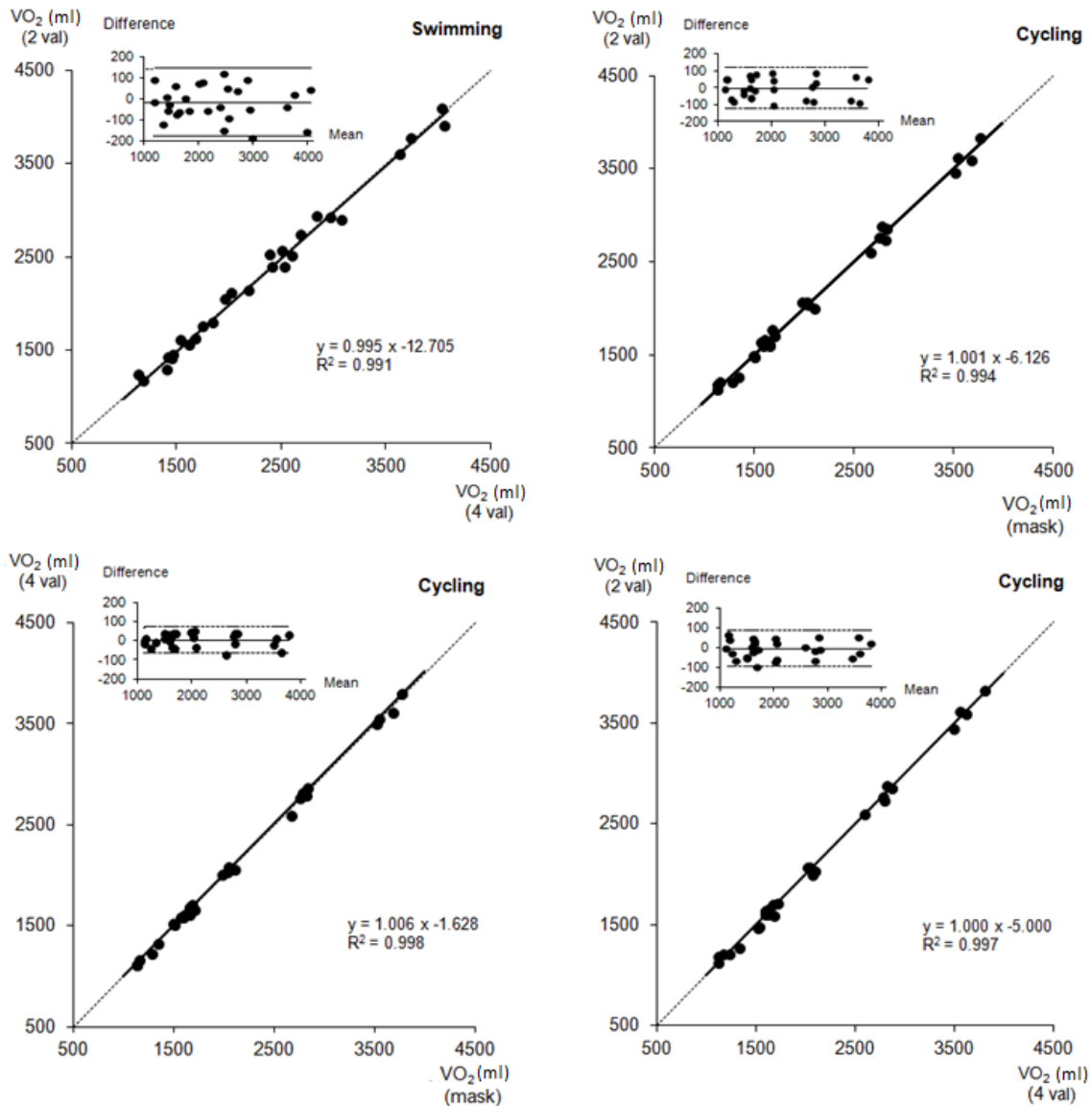


Figure 3. Passing-Bablok regression and difference of oxygen consumption (VO₂) obtained during swimming and cycling tests between the standard mask (Mask), the 2 (SV2) and 4 (SV4) valves. For each one of the four main graphs is reported the Passing-Bablok regression plot (the outside panel), with the linear regression (solid line), the identity (dashed line) and the equation with the Pearson's determinant coefficient (R^2), and the Bland-Altman plot (upper-left panel) with the mean difference (solid lines) and the 95% CI (dashed lines).

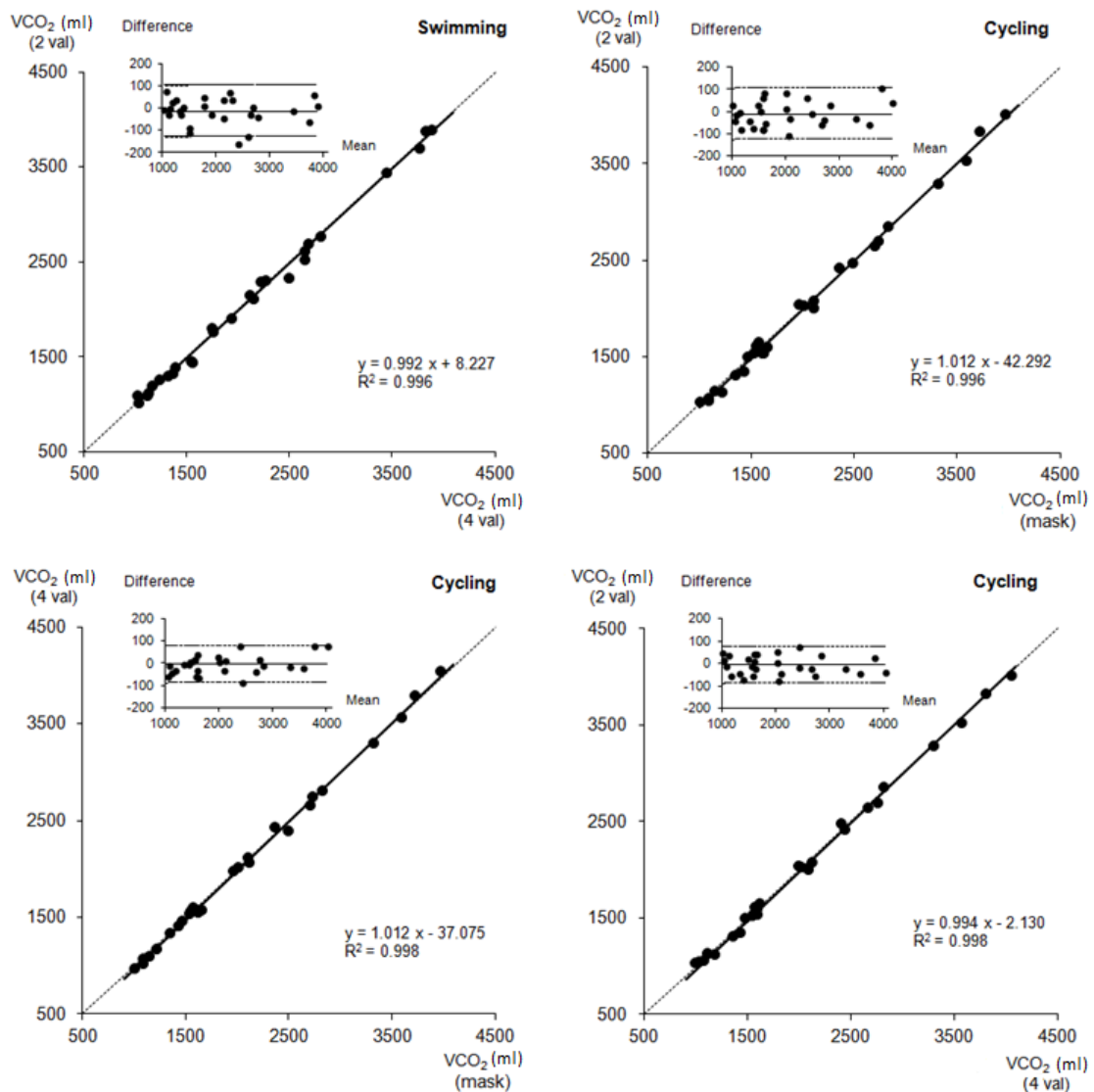


Figure 4. Passing-Bablok regression and difference of carbon dioxide production (VCO_2) obtained during swimming and cycling tests between the standard mask (Mask), the 2 (SV2) and 4 (SV4) valves. For each one of the four main graphs is reported the Passing-Bablok regression plot (the outside panel), with the linear regression (solid line), the identity (dashed line) and the equation with the Pearson's determinant coefficient (R^2), and the Bland-Altman plot (upper-left panel) with the mean difference (solid lines) and the 95% CI (dashed lines).

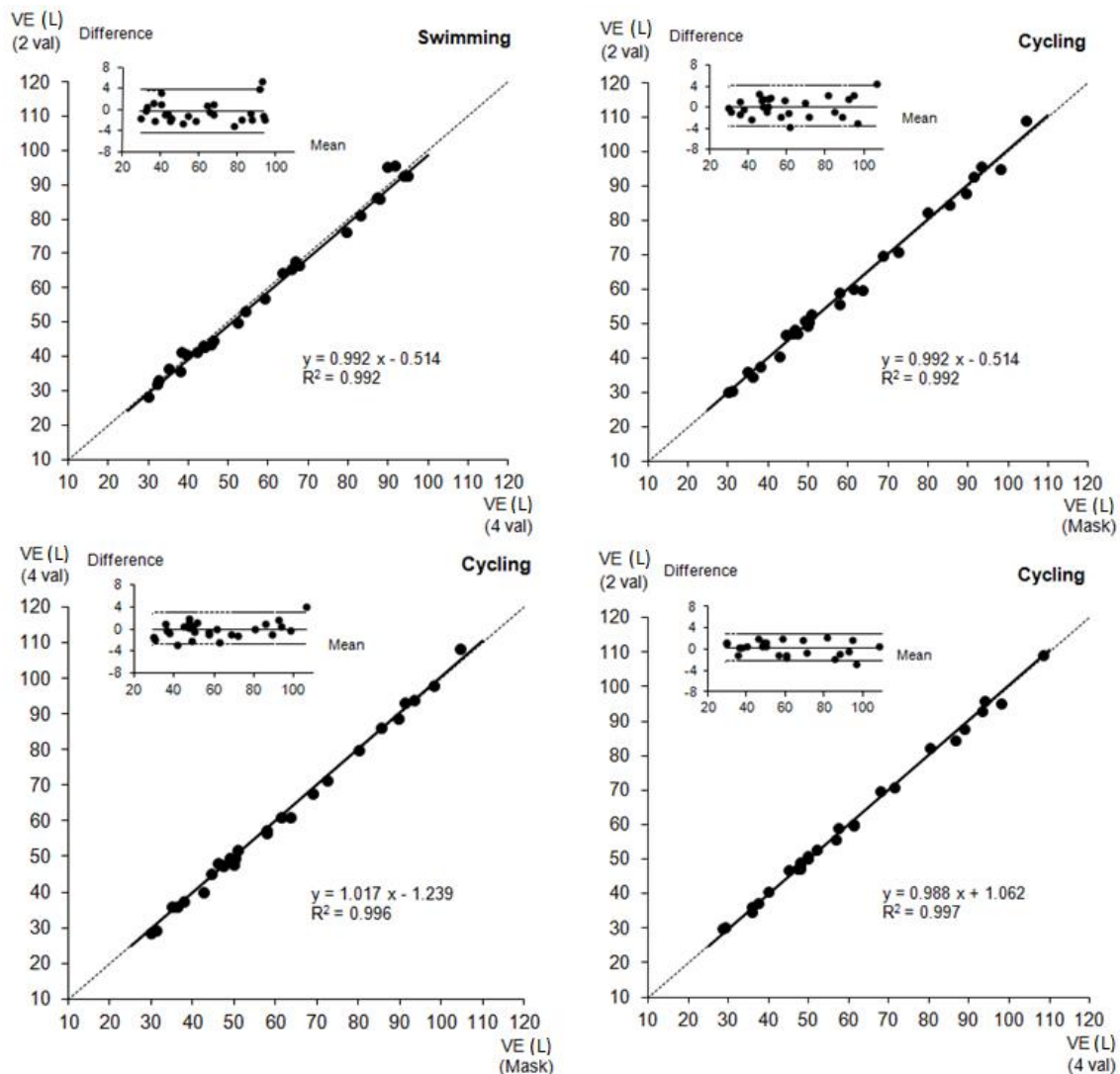


Figure 5. Passing-Bablok regression and difference of Pulmonary ventilation (V_E) obtained during swimming and cycling tests between the standard mask (Mask), the 2 (SV2) and 4 (SV4) valves. For each one of the four main graphs is reported the Passing-Bablok regression plot (the outside panel), with the linear regression (solid line), the identity (dashed line) and the equation with the Pearson's determinant coefficient (R^2), and the Bland-Altman plot (upper-left panel) with the mean difference (solid lines) and the 95% CI (dashed lines).

Discussion

This study demonstrated that the new snorkel AquaTrainer® system with 2 or 4 valves connected with the K4b² telemetric device is comparable with the standard facemask under controlled laboratory conditions for gas analysis.

Moreover, the four valves AquaTrainer® configuration has shown a high correlation to the two valves system, both in ground and aquatic exercise.

Previous studies reported a VO_2 overestimation (~15%) and systematic differences (3-9%) in ventilatory parameters comparing the snorkel with the standard mask (Gayda et al., 2010; Keskinen et al., 2003). Different from those, our results did not report any systematic differences in ventilatory parameters when the new snorkel AquaTrainer® with two or four valves was compared to the Mask. In fact, differently from data reported by Keskinen et al. (2003) who found a 5–7% difference for VO_2 (mean absolute difference was $-174 \text{ mL}\cdot\text{min}^{-1}$ with 95% CI: -198 to $-151 \text{ mL}\cdot\text{min}^{-1}$), our difference was below the 1% (from -0.81 to 0.03 ; 95% CI always included 0) with mean absolute difference in VO_2 ranging from $0.9 \text{ mL}\cdot\text{min}^{-1}$ (95% CI: -66.0 to 67.7 , for Mask vs SV4, cycling) to $-18.7 \text{ mL}\cdot\text{min}^{-1}$ (95% CI: -180.0 to 143.5 , for SV4 vs SV2 swimming). In fact, in this study, an upgrade of the old snorkel AquaTrainer® model and a more painstaking research protocol was used in order to improve the accuracy of data. In fact, as previously reported by other authors (Brugnoli, 2010; Keskinen et al., 2003; Rodriguez et al., 2008), the new AquaTrainer® now has the expiration and inspiration tubes that join at the apex before the turbine, allowing the use of the flowmeter in the standard mode (in/ex hardware configuration for facemask use). Moreover, different from the previous model, in which a closed support for the K4b² was used (see “Tips and suggestion on how to use AQUATRAINER” Cosmed Ltd., 2005: 9-11), the new AquaTrainer® provides an open support system in order to prevent from overheating and samplings of stale air if the auto-calibration is used. In addition, the reduction of the dead space at 11.3 ml and the use of two supplementary valves (SV4), tend to reduce mixtures of gasses at the valves assembly, which might alter the oxygen and carbon dioxide expiratory fractions. Moreover, in order to reduce resistances and air turbulence while breathing, the new AquaTrainer® prototype uses, in comparison to the snorkel of Keskinen et al. (2003), a smooth internal valves assembly surface, two flexible but not stretchable tubes of 35 mm of diameter and 86 cm of length and, larger size Hans-Rudolf valves of 35 mm of

diameter, counting a similar internal volume (847 ml compared to the 825 ml of the previous one). In resting condition the internal volume exceeded the tidal volume running the risk of sampling a mixture of two successive expirations. This problem does not persist during exercise being the expired volume detected at the lower affordable exercise pace in our athletes (data not reported in this paper) higher than 1000 ml. Some other structural modifications that included a soft and oval mouthpiece, a flexible head connection, and flexible – but underwater stable – tubes were made to improve comfort during swimming. At last, the use of a hand-cart that moves the snorkel and K4b² system on a suspended wire along the swimming pool increased the freedom of movement of the swimmer and facilitates the control of the operator. In order to prevent loss of data during tests and obtain accurate data, the auto-calibration was removed from the K4b² settings, and an accurate calibration procedure (that included volumes, gases and delay calibrations) was conducted before each test. Moreover, different from previous studies, the real temperature at the turbine (27°C) was measured and then reported into the K4b² software, instead of an ambient air of 28°C. In previous studies a temperature adjustment was not applied when a snorkel device was used in connection with the K4b² (Gayda et al., 2010; Keskinen et al., 2003; Rodriguez et al., 2008), two of these reporting the existence of a temperature sensor inside the turbine. In these conditions the facemask default temperature of 34°C is automatically assumed by the K4b². In our study we observed an average 6.0°C difference between facemask and the temperature at the turbine when at the snorkel (34.6°C and 27.0°C, respectively); a similar temperature difference could have been responsible for the ~15% $\dot{V}O_2$ overestimation (Gayda et al., 2010) and the 3-9% systematic error of respiratory values reported in previous studies (Keskinen et al., 2003; Rodriguez et al., 2008).

Ventilatory parameters ($\dot{V}O_2$, $\dot{V}CO_2$, V_E , V_T) and expiratory fraction of O_2 and CO_2 reported no differences between conditions in our study. The R^2 coefficient was very high ($R^2 \geq 0.991$) in $\dot{V}O_2$, $\dot{V}CO_2$, V_E , and high in V_T ($0.947 \geq R^2 \geq 0.914$), F_{EO_2} and F_{ECO_2} ($0.904 \geq R^2 \geq 0.826$). With respect to previous studies, these

values are higher than reported by Keskinen et al. (2003) on humans while $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{V}_T were only slightly lower and \dot{V}_E higher compared to the study of Rodriguez et al. (2008), where a gas exchange simulator system was used. Moreover, the current results reported, for each parameter, a 95% CI that contains the value 1 for the slope and the 0 for the intercept. According to these results, this is the first study that rejects both proportional and fixed difference hypotheses when validating a snorkel device, in connection to the K4b² analyzer. In fact, Keskinen et al. (2003) and Rodriguez et al. (2008) obtained a good R^2 in ventilatory parameters, but both proportional and fixed differences were rarely valorized. These results, regarding the previously mentioned 3-9% systematic error in volumes comparing the snorkel and the standard conditions, are in line with our hypothesis of a mistake in reporting the temperature of the expired gas. Therefore, temperature measure at the turbine is recommended, since it does not have any temperature sensors. In fact, the manufacturer recommends adjusting the temperature with the ambient value when a snorkel is used. Our results demonstrate that, in order to have more accurate gas exchange values, data should be adjusted to the real temperature of expired gas but for indoor swimming pools with controlled environment it may not be necessary.

The use of four valves to prevent mixture between expired and ambient air has been shown irrelevant since that a high agreement between SV4 and SV2 was reported in both conditions and for all studied parameters. No studies previously analyzed the difference between a 2 and a 4 valve snorkel making necessary the control of this variable using a snorkel with removable valves. The R^2 coefficient was between 0.920 and 0.996 in ventilatory parameters, and 0.826, 0.894 and 0.991 in F_{EO_2} , F_{ECO_2} and HR, respectively, when cycling; in swimming, R^2 was between 0.938 and 0.998 in ventilatory parameters, and equal to 0.856, 0.836 and 0.987 in F_{EO_2} , F_{ECO_2} and HR, respectively. Furthermore, the 95% CI in all parameters reject the proportional and the fixed difference hypotheses. Therefore, since the addition of two additional valves does not affect cardiorespiratory parameters, the two valves model is preferred.

The new AquaTrainer® system was defined by all subjects as more comfortable in comparison with the previous systems mainly because of: a) the softer and more comfortable mouthpiece and head connection, b) the underwater stability of the tubes, c) a higher ductility of the system, in terms of freedom of movements and, comparing the SV2 with SV4 AquaTrainer® prototype, d) a subjective better comfort using the two valves model.

In conclusion, the obtainment of a high correlation between SV2, SV4 and Mask in cycling, and SV2 and SV4 in swimming, let us to conclude that the new AquaTrainer® system is suitable for collecting respiratory gasses in swimming, and constitute an improvement regarding previous available systems.

Practical Notes

The new AquaTrainer® snorkel will allow trainers and researchers to perform VO_2 assessment in swimming with high precision and comfort. However, as all the previous model, swimmers need a familiarization period in order to feel comfortable with the device. To have more accurate gas exchange values, trainer should control and use the ambient temperature or, if possible, the temperature at the turbine as reference value. Thanks to its flexible and anatomic structure the new AquaTrainer® snorkel can adapt to swimmers in different positions. A preliminary test we conducted, reported no evident limits nor subjects relevant discomforts while using the new AquaTrainer® prototype with different techniques. However, further studies are needed to test the validity of this device while different swimming techniques are used.

References

Chapter 1

- Alberty, M., Sidney, M., Huot-Marchand, F., Hespel, J. M., & Pelayo, P. (2005). Intracyclic velocity variations and arm coordination during exhaustive exercise in front crawl stroke. *International Journal of Sports Medicine*, 26(6), 471-475.
- Barbosa, T., Fernandes, R., Keskinen, K. L., Colaço, P., Cardoso, C., Silva, J., & Vilas-Boas, J. P. (2006). Evaluation of the energy expenditure in competitive swimming strokes. *International Journal of Sports Medicine*, 27(11), 894-899.
- Barbosa, T., Santos Silva, J. V., Sousa, F., & Vilas-Boas, J. P. (2003). Comparative study of the response of kinematical variables from the hip and the center of mass in butterfly. In J. C. Chatard (Ed.), *Biomechanics and Medicine in Swimming IX* (pp. 93-98). St Etienne: University of St Etienne Publications.
- Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010a). Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. *Journal of Science and Medicine in Sport*, 13(2), 262-269.
- Barbosa, T. M., Costa, M., Marinho, D. A., Coelho, J., Moreira, M., & Silva, A. J. (2010b). Modeling the links between young swimmers' performance: Energetic and biomechanical profiles. *Pediatric Exercise Science*, 22(3), 379-391.
- Bonifazi, M., Martelli, G., Marugo, L., Sardella, F., & Carli, G. (1993). Blood lactate accumulation in top level swimmers following competition. *J Sports Med Phys Fitness*, 33(1), 13-18.
- Chollet, D., Chabies, S., & Chatard, J. C. (2000). A new index of coordination for the crawl: Description and usefulness. *International Journal of Sports Medicine*, 21(1), 54-59.
- Chollet, D., Delaplace, C., Pelayo, P., Tourny, C., & Sidney, M. (1997). Stroking characteristic variations in the 100-M freestyle for male swimmers of differing skill. *Perceptual and Motor Skills*, 85(1), 167-177.
- Costill, D. L., Maglischo, E. W., & Richardson, A. B. (1992). *Swimming* (4th ed.). Bodmin, UK: Blackwell Science LTD.
- Craig, A. B., & Pendergast, D. R. (1979). Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. *Medicine and Science in Sports and Exercise*, 11(3), 278-283.
- Craig, A. B., Skehan, P. L., Pawelczyk, J. A., & Boomer, W. L. (1985). Velocity, stroke rate, and distance per stroke during elite swimming competition. *Medicine and Science in Sports and Exercise*, 17(6), 625-634.
- Fernandes, R. (2006). *Time limit at the minimum velocity corresponding to VO_{2max} : Characterizations and determinant factors*. Porto: University of Porto Doctoral Thesis in Sports Sciences.
- Fernandes, R. J., Billat, V. L., Cruz, A. C., Colaço, P. J., Cardoso, C. S., & Vilas-Boas, J. P. (2006). Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity? *Journal of Sports Medicine and Physical Fitness*, 46(3), 373-380.
- Fernandes, R. J., Keskinen, K. L., Colaço, P., Querido, A. J., Machado, L. J., Morais, P. A., Novais, D. Q., Marinho, D. A., & Vilas Boas, J. P. (2008). Time limit at VO_{2max} velocity in elite crawl swimmers. *International Journal of Sports Medicine*, 29(2), 145-150.
- Fernandes, R. J., Sousa, M., Pinheiro, A., Vilar, S., Colaço, P., & Vilas-Boas, J. P. (2010). Assessment of individual anaerobic threshold and stroking parameters in swimmers aged 10-11 years. *European Journal of Sport Science*, 10(5), 311-317.
- Figueiredo, P. (2011). *Biophysical Analysis of the 200 m Front Crawl. The interplay between the biomechanical, energetic, coordinative, and muscular factors*. Porto: University of Porto. Doctoral Thesis in Sports Sciences.
- Figueiredo, P., Barbosa, T. M., Vilas-Boas, J. P., & Fernandes, R. J. (2012). Energy cost and body centre of mass' 3D intracycle velocity variation in swimming. *European Journal of Applied Physiology*, 112(9), 3319-3326.
- Figueiredo, P., Morais, P., Vilas-Boas, J. P., & Fernandes, R. J. (2013a). Changes in arm coordination and stroke parameters on transition through the lactate threshold.

- European Journal of Applied Physiology*, 113(8), 1957-1964.
- Figueiredo, P., Nazario, R., Sousa, M., Pelarigo, J. G., Vilas-Boas, J. P., & Fernandes, R. (2014). Kinematical analysis along maximal lactate steady state swimming intensity. *Journal of Sports Science and Medicine*, 13(3), 610-615.
- Figueiredo, P., Rouard, A., Vilas-Boas, J. P., & Fernandes, R. J. (2013b). Upper- and lower-limb muscular fatigue during the 200-m front crawl. *Applied Physiology, Nutrition and Metabolism*, 38(7), 716-724.
- Figueiredo, P., Toussaint, H. M., Vilas-Boas, J. P., & Fernandes, R. J. (2013c). Relation between efficiency and energy cost with coordination in aquatic locomotion. *European Journal of Applied Physiology*, 113(3), 651-659.
- Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J. P., & Fernandes, R. J. (2011). An energy balance of the 200 m front crawl race. *European Journal of Applied Physiology*, 111(5), 767-777.
- Fitts, R. H. (1994). Cellular mechanisms of muscle fatigue. *Physiological reviews*, 74(1), 49-94.
- Gourgoulis, V., Aggeloussis, N., Boli, A., Michalopoulou, M., Toubekis, A., Kasimatis, P., Vezos, N., Mavridis, G., Antoniou, P., & Mavrommatis, G. (2013). Inter-arm coordination and intra-cyclic variation of the hip velocity during front crawl resisted swimming. *Journal of Sports Medicine and Physical Fitness*, 53(6), 612-619.
- Havriluk, R. (2007). Variability in measurement of swimming forces: A meta-analysis of passive and active drag. *Research Quarterly for Exercise and Sport*, 78(2), 32-39.
- Holmer, I. (1974). Energy cost of arm stroke, leg kick, and the whole stroke in competitive swimming styles. *European Journal of Applied Physiology and Occupational Physiology*, 33(2), 105-118.
- Lavoie, J. M., & Montpetit, R. R. (1986). Applied physiology of swimming. *Sports Medicine*, 3, 165-189.
- Maglischo, E. W. (2003). *Swimming fastest: The essential reference on technique, training, and program design*. Champaign, IL: Human Kinetics Publisher.
- Olbrecht, J. (2000). *The science of winning. Planning, periodizing and optimizing swim training*. Luton: Swimshop.
- Oliveira, M. F. M., Caputo, F., Lucas, R. D., Denadai, B. S., & Greco, C. C. (2012). Physiological and stroke parameters to assess aerobic capacity in swimming. *International Journal of Sports Physiology and Performance*, 7(3), 218-223.
- Pendergast, D. R., Capelli, C., Craig, A., Di Prampero, P. E., Minetti, A. E., Mollendorf, J., Termin, A., & Zamparo, P. (2006). Biophysics in swimming. In J. P. Vilas-Boas, F. Alves & A. Marques (Eds.), *Xth International Symposium of Biomechanics and Medicine in Swimming* (pp. 185-189). Porto, Portugal.
- Pendergast, D. R., & Lundgren, C. E. (2009). The underwater environment: cardiopulmonary, thermal, and energetic demands. *Journal of Applied Physiology* 106(1), 276-283.
- Pendergast, D. R., Moon, R. E., Krasney, J. J., Held, H. E., & Zamparo, P. (2015). Human Physiology in an Aquatic Environment. *Comprehensive Physiology*, 5(4), 1705-1750.
- Peyrebrune, M. C., Toubekis, A. G., Lakomy, H. K. A., & Nevill, M. E. (2014). Estimating the energy contribution during single and repeated sprint swimming. *Scandinavian Journal of Medicine & Science in Sports*, 24(2), 369-376.
- Psycharakis, S. G., Cooke, C. B., Paradisis, G. P., O'Hara, J., & Phillips, G. (2008). Analysis of selected kinematic and physiological performance determinants during incremental testing in elite swimmers. *Journal of Strength and Conditioning Research*, 22(3), 951-957.
- Psycharakis, S. G., Naemi, R., Connaboy, C., McCabe, C., & Sanders, R. H. (2010). Three-dimensional analysis of intracycle velocity fluctuations in frontcrawl swimming. *Scandinavian Journal of Medicine and Science in Sports*, 20(1), 128-135.
- Psycharakis, S. G., & Sanders, R. H. (2008). Shoulder and hip roll changes during 200-m front crawl swimming. *Medicine and Science in Sports and Exercise*, 40(12), 2129-2136.
- Psycharakis, S. G., & Sanders, R. H. (2009). Validity of the use of a fixed point for intracycle velocity calculations in swimming. *Journal of Science and Medicine in Sport* 12(2), 262-265.
- Pyne, D. B., Lee, H., & Swanwick, K. M. (2001). Monitoring the lactate threshold in world-ranked swimmers. *Medicine and Science in Sports and Exercise*, 33(2), 291-297.
- Pyne, D. B., & Sharp, R. L. (2014). Physical and energy requirements of competitive swimming

- events. *International Journal of Sport Nutrition and Exercise Metabolism*, 24(4), 351-359.
- Schnitzler, C., Seifert, L., Alberty, M., & Chollet, D. (2010). Hip Velocity and Arm Coordination in Front Crawl Swimming. *International Journal of Sports Medicine*, 31, 875-881.
- Schnitzler, C., Seifert, L., Ernwein, V., & Chollet, D. (2008). Arm coordination adaptations assessment in swimming. *International Journal of Sports Medicine*, 29(6), 480-486.
- Seifert, L. (2010). Inter-Limb Coordination in Swimming In P. L. Kjendlie, R. K. Stallman & J. Cabri (Eds.), *XIth International Symposium for Biomechanics and Medicine in Swimming* (pp. 35-39). Oslo: Norwegian School of Sport Science.
- Seifert, L., Chollet, D., & Bardy, B. G. (2004). Effect of swimming velocity on arm coordination in the front crawl: A dynamic analysis. *Journal of Sports Sciences*, 22(7), 651-660.
- Seifert, L., Chollet, D., & Chatard, J. C. (2007). Kinematic changes during a 100-m front crawl: Effects of performance level and gender. *Medicine and Science in Sports and Exercise*, 39(10), 1784-1793.
- Seifert, L., Schnitzler, C., Bideault, G., Alberty, M., Chollet, D., & Toussaint, H. M. (2015). Relationships between coordination, active drag and propelling efficiency in crawl. *Human Movement Science*, 39, 55-64.
- Smith, D. J., Norris, S. R., & Hogg, J. M. (2002). Performance evaluation of swimmers: Scientific tools. *Sports Medicine*, 32(9), 539-554.
- Soares, S. M., Fernandes, R. J., Machado, J. L., Maia, J. A., Daly, D. J., & Vilas-Boas, J. P. (2014). Assessment of fatigue thresholds in 50-m all-out swimming. *International Journal of Sports Physiology and Performance*, 9(6), 959-965.
- Sousa, A., Figueiredo, P., Pendergast, D., Kjendlie, P., Vilas-Boas, J., & Fernandes, R. (2014a). Critical Evaluation of Oxygen Uptake Assessment in Swimming. *International Journal of Sports Physiology and Performance*, 9(2), 190-202.
- Sousa, A., Vilas Boas, J. P., & Fernandes, R. J. (2014b). VO₂ Kinetics and Metabolic Contributions Whilst Swimming at 95, 100, and 105% of the Velocity at VO₂max. *BioMed Research International*, doi: 10.1155/2014/675363.
- Toussaint, H., & Beek, P. (1992). Biomechanics of competitive front crawl swimming. *Sports Medicine*, 13 (1), 8-24.
- Toussaint, H. M., Beelen, A., Rodenburg, A., Sargeant, A. J., De Groot, G., Hollander, A. P., & Van Ingen Schenau, G. J. (1988a). Propelling efficiency of front-crawl swimming. *Journal of Applied Physiology*, 65(6), 2506-2512.
- Toussaint, H. M., de Groot, G., Savelberg, H. H. C. M., Vervoorn, K., Hollander, A. P., & Van Ingen Schenau, G. J. (1988b). Active drag related to velocity in male and female swimmers. *Journal of Biomechanics*, 21 (5), 435-438.
- Toussaint, H. M., & Hollander, A. P. (1994). Energetics of competitive swimming: Implications for training programmes. *Sports Medicine*, 18(6), 384-405.
- Toussaint, H. M., Roos, P. E., & Kolmogorov, S. (2004). The determination of drag in front crawl swimming. *Journal of Biomechanics*, 37(11), 1655-1663.
- Vilas-Boas, J. P. (1993). *Biophysical characterization of the three breaststroke variants* Porto: University of Porto. Doctoral Thesis in Sports Sciences.
- Vilas-Boas, J. P. (2010). Biomechanics and Medicine in Swimming, Past, Present and Future. In P. L. Kjendlie, R. K. Stallman & J. Cabri (Eds.), *XIth International Symposium for Biomechanics and Medicine in Swimming* (pp. 12-19). Oslo: Norwegian School of Sport Science.
- Vilas-Boas, J. P., Fernandes, R. J., & Barbosa, T. M. (2010). Intra-cycle velocity variations, swimming economy, performance and training in swimming. In L. Seifert, D. Chollet & I. Mujika (Eds.), *World book of swimming: from science to performance* (pp. 120-140). New York: Nova Science Publishers, Inc.
- Vilas-Boas, J. P., & Santos, P. (1994). Comparison of swimming economy in three breaststroke techniques. In M. Miyashita, Y. Mutoh & A. Richardson (Eds.), *Medicine and Science in Aquatic Sports—10th FINA World Sport Medicine Congress* (pp. 104-109). Honolulu: HI: Karger.
- Zamparo, P. (2011). Assessing gross efficiency and propelling efficiency in swimming. *Portuguese Journal of Sports Science*, 11(Suppl 3), 65-68.
- Zamparo, P., Capelli, C., & Pendergast, D. (2011). Energetics of swimming: A historical perspective. *European Journal of Applied Physiology*, 111(3), 367-378.

- Zamparo, P., & Swaine, I. L. (2012). Mechanical and propelling efficiency in swimming derived from exercise using a laboratory-based whole-body swimming ergometer. *Journal of Applied Physiology*, 113(4), 584-594.
- Zamparo, P., Turri, E., Peterson Silveira, R., & Poli, A. (2014). The interplay between arms-only propelling efficiency, power output and speed in master swimmers. *European Journal of Applied Physiology*, 114(6), 1259-1268.

Chapter 2

- Alberty, M., Sidney, M., Huot-Marchand, F., Hespel, J. M., & Pelayo, P. (2005). Intracyclic velocity variations and arm coordination during exhaustive exercise in front crawl stroke. *International Journal of Sports Medicine*, 26(6), 471-475.
- Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010). Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. *Journal of Science and Medicine in Sport*, 13(2), 262-269.
- Berger, M. A. M., Hollander, A. P., & De Groot, G. (1999). Determining propulsive force in front crawl swimming: A comparison of two methods. *Journal of Sports Sciences*, 17(2), 97-105.
- Cabri, J. M. H., Annemans, L., Clarys, J.P., Bollens, E., & Publie, J. (1988). The relation of stroke frequency, force, and EMG in front crawl tethered swimming. In K. W. B. E. Ungerechts, K. Reischle (Ed.), *Swimming Science V* (pp. 183-189). Champaign, Illinois: Human Kinetics Publishers.
- Chollet, D., Chabies, S., & Chatard, J. C. (2000). A new index of coordination for the crawl: Description and usefulness. *International Journal of Sports Medicine*, 21(1), 54-59.
- Craig, A. B., & Pendergast, D. R. (1979). Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. *Medicine and Science in Sports and Exercise*, 11(3), 278-283.
- D'Acquisto, L. J., & Costill, D. L. (2000). Relationship between intracyclic linear body velocity fluctuations, power and sprint breaststroke performance. *Swimming In Australia*, 16(1), 65-71.
- Fernandes, R., Ribeiro, J., Figueiredo, P., Seifert, L., & Vilas-Boas, J. P. (2012). Kinematics of the Hip and Body Center of Mass in Front Crawl. *Journal of Human Kinetics*, 33, 15-23.
- Fernandes, R. J., Billat, V. L., Cruz, A. C., Colaço, P. J., Cardoso, C. S., & Vilas-Boas, J. P. (2006). Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity? *Journal of Sports Medicine and Physical Fitness*, 46(3), 373-380.
- Figueiredo, P., Kjendlie, P. L., Vilas-Boas, J. P., & Fernandes, R. J. (2012). Intracycle Velocity Variation of the Body Centre of Mass in Front Crawl. *Int J Sports Med.*, 33(04), 285-290.
- Figueiredo, P., Morais, P., Vilas-Boas, J. P., & Fernandes, R. J. (2013a). Changes in arm coordination and stroke parameters on transition through the lactate threshold. *European Journal of Applied Physiology*, 113(8), 1957-1964.
- Figueiredo, P., Pendergast, D. R., Vilas-Boas, J. P., & Fernandes, R. J. (2013b). Interplay of biomechanical, energetic, coordinative, and muscular factors in a 200 m front crawl swim. *BioMed Research International*. doi: 10.1155/2013/897232.
- Martin, R. B., Yeater, R. A., & White, M. K. (1981). A simple analytical model for the crawl stroke. *Journal of Biomechanics*, 14(8), 539-548.
- Minetti, A. E. (2000). The three modes of terrestrial locomotion. In M. B. Nigg B, Mester J (Ed.), *Biomechanics and Biology of movement* (pp. 67-78). Illinois: Human Kinetics.
- Nigg, B. M. (1983). Selected methodology in biomechanics with respect to swimming. In H. P. Hollander AP, Groot Gd (Ed.), *Biomechanics and Medicine in Swimming* (pp. 72-80). Champaign, Illinois: Human Kinetics Publishers.
- Schnitzler, C., Seifert, L., Ernwein, V., & Chollet, D. (2008). Arm coordination adaptations assessment in swimming. *International Journal of Sports Medicine*, 29(6), 480-486.
- Seifert, L., & Chollet, D. (2009). Modelling spatial-temporal and coordinative parameters in swimming. *Journal of Science and Medicine in Sport*, 12(4), 495-499.
- Seifert, L., Chollet, D., & Chatard, J. C. (2007). Kinematic changes during a 100-m front crawl:

- Effects of performance level and gender. *Medicine and Science in Sports and Exercise*, 39(10), 1784-1793.
- Seifert, L., Toussaint, H. M., Alberty, M., Schnitzler, C., & Chollet, D. (2010). Arm coordination, power, and swim efficiency in national and regional front crawl swimmers. *Human Movement Science*, 29(3), 426-439.
- Toussaint, H. M., Carol, A., Kranenborg, H., & Truijens, M. J. (2006). Effect of fatigue on stroking characteristics in an arms-only 100-m front-crawl race. *Medicine and Science in Sports and Exercise*, 38(9), 1635-1642.
- Toussaint, H. M., de Groot, G., Savelberg, H. H. C. M., Vervoorn, K., Hollander, A. P., & Van Ingen Schenau, G. J. (1988). Active drag related to velocity in male and female swimmers. *Journal of Biomechanics*, 21(5), 435-438.
- Toussaint, H. M., Knops, W., De Groot, G., & Hollander, A. P. (1990). The mechanical efficiency of front crawl swimming. *Medicine and Science in Sports and Exercise*, 22(3), 402-408.
- Toussaint, H. M., Roos, P. E., & Kolmogorov, S. (2004). The determination of drag in front crawl swimming. *Journal of Biomechanics*, 37(11), 1655-1663.
- Zamparo, P., Pendergast, D. R., Mollendorf, J., Termin, A., & Minetti, A. E. (2005). An energy balance of front crawl. *European Journal of Applied Physiology*, 94(1-2), 134-144.

Chapter 3

- Baldari, C., Fernandes, R. J., Meucci, M., Ribeiro, J., Vilas-Boas, J. P., & Guidetti, L. (2013). Is the new AquaTrainer® snorkel valid for VO₂ assessment in swimming? *International Journal of Sports Medicine*, 34(4), 336-344.
- Barbosa, T., Silva, A. J., Reis, A. M., Costa, M., Garrido, N., Policarpo, F., & Reis, V. M. (2010). Kinematical changes in swimming front crawl and breaststroke with the AquaTrainer® snorkel. *European Journal of Applied Physiology*, 109(6), 1155-1162.
- Bentley, D. J., Roels, B., Hellard, P., Fauquet, C., Libicz, S., & Millet, G. P. (2005). Physiological responses during submaximal interval swimming training: Effects of interval duration. *Journal of Science and Medicine in Sport*, 8(4), 392-402.
- Bland, J. M., & D.G., A. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*, 1, 307-310.
- Conceição, A., Silva, A. J., Boaventura, J., Marinho, D. A., & Louro, H. (2013). Wave characteristics in breaststroke technique with and without snorkel use. *Journal of Human Kinetics*, 39(1), 185-194.
- Dal Monte, A., Sardella, F., Alippi, B., Faina, M., & Manetta, A. (1994). A new respiratory valve system for measuring oxygen uptake during swimming. *European Journal of Applied Physiology* 69(2), 159-162.
- de Jesus, K., Guidetti, L., de Jesus, K., Vilas-Boas, J. P., Baldari, C., & Fernandes, R. J. (2014). Which are the best VO₂ sampling intervals to characterize low to severe swimming intensities? *International Journal of Sports Medicine*, DOI: 10.1055/s-0034-1368784.
- Di Prampero, P. E., Pendergast, D. R., Wilson, D. W., & Rennie, D. W. (1974). Energetics of swimming in man. *Journal of Applied Physiology*, 37(1), 1-5.
- Fernandes, R. J., Figueiredo, P., & Vilas-Boas, J. P. (2013). About the use and conclusions extracted from a single tube snorkel used for respiratory data acquisition during swimming. *Journal of Physiological Sciences*, 63(2), 155-157.
- Gayda, M., Bosquet, L., Juneau, M., Guiraud, T., Lambert, J., & Nigam, A. (2010). Comparison of gas exchange data using the Aquatrainer® system and the facemask with Cosmed K4b2 during exercise in healthy subjects. *European Journal of Applied Physiology*, 109(2), 191-199.
- Harriss, D. J., & Atkinson, G. (2013). Ethical standards in sport and exercise science research: 2014 update. *International Journal of Sports Medicine*, 34(12), 1025-1028.
- Hollander, A. P., Toussaint, H. M., De Groot, G., & Van Ingen Schenau, G. J. (1985). Active drag and swimming performance. *New Zealand Journal of Sports Medicine*, 13 (3), 110-113.
- Keskinen, K., Rodríguez, F., Kusch, M., & Hoffmann, U. (2002). Validity of breath-by-breath spirometric measurements with two swimming snorkels assessed by a gas exchange

- simulation system. In J. C. Chatard. (Ed.), *Book of abstracts of IX Biomechanics and Medicine in Swimming* (pp. 95). Saint-Étienne: Publications de l'Université de Saint-Étienne.
- Keskinen, K. L., Rodriguez, F. A., & Keskinen, O. P. (2003). Respiratory snorkel and valve system for breath-by-breath gas analysis in swimming. *Scandinavian Journal of Medicine and Science in Sports*, 13(5), 322-329.
- Kjendlie, P. L., Stallman, R., & Gundersen, J. s. (2003). Influences of a Breathing Valve on Swimming Technique. In J. C. Chatard. (Ed.), *Biomechanics and Medicine in Swimming IX* (pp. 69-74). Saint-Étienne: Publications de l'Université de Saint-Étienne.
- Kolmogorov, S. V., & Duplishcheva, O. A. (1992). Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. *Journal of Biomechanics*, 25(3), 311-318.
- Komar, J., Leprêtre, P. M., Alberty, M., Vantorre, J., Fernandes, R. J., Hellard, P., Chollet, D., & Seifert, L. (2012). Effect of increasing energy cost on arm coordination in elite sprint swimmers. *Human Movement Science*, 31(3), 620-629.
- Lyttle, A. D., Blanksby, B. A., Elliott, B. C., & Lloyd, D. G. (1998). The effect of depth and velocity on drag during the streamlined glide. *Journal of Swimming Research*, 13, 15-22.
- Mollendorf, J. C., Termin li, A. C., Oppenheim, E., & Pendergast, D. R. (2004). Effect of swim suit design on passive drag. *Medicine and Science in Sports and Exercise*, 36(6), 1029-1035.
- Passing, H., & Bablok, W. (1983). A new biometrical procedure for testing the equality of measurements from two different analytical methods. Application of linear regression procedures for method comparison studies in clinical chemistry. Part I. *Journal of Clinical Chemistry and Clinical Biochemistry*, 21(11), 709-720.
- Pendergast, D. R., Capelli, C., Craig, A., Di Prampero, P. E., Minetti, A. E., Mollendorf, J., Termin, A., & Zamparo, P. (2006). Biophysics in swimming. In J. P. Vilas-Boas, F. Alves & A. Marques (Eds.), *Xth International Symposium of Biomechanics and Medicine in Swimming* (pp. 185-189). Porto, Portugal.
- Pitman, E. J. G. (1939). A note on normal correlation. *Biometrika*, 31, 9-12.
- Ribeiro, J., De Jesus, K., Figueiredo, P., Toussaint, H., Guidetti, L., Alves, F., Vilas-Boas, J., & Fernandes, R. (2013). Biomechanical determinants of force production in front crawl swimming. *Journal of Sports Medicine and Physical Fitness* 53(3 suppl 1), 30-37.
- Rodriguez, F. A., Keskinen, K. L., Kusch, M., & Hoffmann, U. (2008). Validity of a swimming snorkel for metabolic testing. *International Journal of Sports Medicine*, 29(2), 120-128.
- Schreven, S., Toussaint, H. M., Smeets, J. B. J., & Beek, P. J. (2013). The effect of different inter-pad distances on the determination of active drag using the Measuring Active Drag system. *Journal of Biomechanics*, 46(11), 1933-1937.
- Seifert, L., Komar, J., Leptré, P. M., Lemaitre, F., Chavallard, F., Alberty, M., Houel, N., Hausswirth, C., Chollet, D., & Hellard, P. (2010). Swim specialty affects energy cost and motor organization. *International Journal of Sports Medicine*, 31(9), 624-630.
- Sousa, A., Figueiredo, P., Pendergast, D., Kjendlie, P., Vilas-Boas, J., & Fernandes, R. (2014a). Critical Evaluation of Oxygen Uptake Assessment in Swimming. *International Journal of Sports Physiology and Performance*, 9(2), 190-202.
- Sousa, A., Vilas Boas, J. P., & Fernandes, R. J. (2014b). VO2 Kinetics and Metabolic Contributions Whilst Swimming at 95, 100, and 105% of the Velocity at VO2max. *BioMed Research International*, doi: 10.1155/2014/675363.
- Toussaint, H. M., Beelen, A., Rodenburg, A., Sargeant, A. J., De Groot, G., Hollander, A. P., & Van Ingen Schenau, G. J. (1988). Propelling efficiency of front-crawl swimming. *Journal of Applied Physiology*, 65(6), 2506-2512.
- Toussaint, H. M., Meulemans, A., de Groot, G., Hollander, A. P., Schreurs, A. W., & Vervoorn, K. (1987). Respiratory valve for oxygen uptake measurements during swimming. *European Journal of Applied Physiology* 56(3), 363-366.
- Toussaint, H. M., Roos, P. E., & Kolmogorov, S. (2004). The determination of drag in front crawl swimming. *Journal of Biomechanics*, 37(11), 1655-1663.
- Vennell, R., Pease, D., & Wilson, B. (2006). Wave drag on human swimmers. *Journal of Biomechanics*, 39(4), 664-671.

Chapter 4

- Anderson, G. S., & Rhodes, E. C. (1991). Relationship between blood lactate and excess CO₂ in elite cyclists. *Journal of Sports Sciences*, 9(2), 173-181.
- Aspenes, S. T., & Karlsen, T. (2012). Exercise-training intervention studies in competitive swimming. *Sports Medicine*, 42(6), 527-543.
- Baldari, C., Fernandes, R. J., Meucci, M., Ribeiro, J., Vilas-Boas, J. P., & Guidetti, L. (2013). Is the new AquaTrainer® snorkel valid for VO₂ assessment in swimming? *International Journal of Sports Medicine*, 34(4), 336-344.
- Bunc, V., Heller, J., Leso, J., Sprynarova, S., & Zdanowicz, R. (1987). Ventilatory threshold in various groups of highly trained athletes. *International Journal of Sports Medicine*, 8(4), 275-280.
- Busse, M. W., Scholz, J., & Maassen, N. (1992). Plasma Potassium and ventilation during incremental exercise in humans - Modulation by Sodium-Bicarbonate and substrate availability. *European Journal of Applied Physiology and Occupational Physiology*, 65(4), 340-346.
- Di Prampero, P. E. (1986). The energy-cost of human locomotion on land and in water. *International Journal of Sports Medicine*, 7(2), 55-72.
- Edwards, A., Clark, N., & Macfadyen, A. (2003). Lactate and ventilatory thresholds reflect the training status of professional soccer players where maximum aerobic power is unchanged. *Journal of Sports Science and Medicine*, 2, 23-29.
- Faude, O., Kindermann, W., & Meyer, T. (2009). Lactate Threshold Concepts How Valid are They? *Sports Medicine*, 39(6), 469-490.
- Fernandes, R. J., Cardoso, C. S., Soares, S. M., Ascensao, A., Colaço, P. J., & Vilas-Boas, J. P. (2003). Time Limit and VO₂ Slow Component at Intensities Corresponding to VO_{2max} in Swimmers. *International Journal of Sports Medicine*, 24(8), 576-581.
- Fernandes, R. J., Keskinen, K. L., Colaço, P., Querido, A. J., Machado, L. J., Morais, P. A., Novais, D. Q., Marinho, D. A., & Vilas Boas, J. P. (2008). Time limit at VO_{2max} velocity in elite crawl swimmers. *International Journal of Sports Medicine*, 29(2), 145-150.
- Fernandes, R. J., Sousa, M., Machado, L., & Vilas-Boas, J. P. (2011). Step Length and Individual Anaerobic Threshold Assessment in Swimming. *International Journal of Sports Medicine*, 32(12), 940-946.
- Gastin, P. B. (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Medicine*, 31(10), 725-741.
- Hagberg, J. M., Coyle, E. F., Carroll, J. E., Miller, J. M., Martin, W. H., & Brooke, M. H. (1982). Exercise Hyperventilation in patients with MCardles disease. *Journal of Applied Physiology*, 52(4), 991-994.
- Heinicke, K., Wolfarth, B., Winchenbach, P., Biermann, B., Schmid, A., Huber, G., Friedmann, B., & Schmidt, W. (2001). Blood volume and hemoglobin mass in elite athletes of different disciplines. *International Journal of Sports Medicine*, 22(7), 504-512.
- Holmer, I. (1974). Physiology of swimming man. *Acta Physiologica Scandinavica*, 91(Sup.407), 1-55.
- Hopker, J. G., Jobson, S. A., & Pandit, J. J. (2011). Controversies in the physiological basis of the 'anaerobic threshold' and their implications for clinical cardiopulmonary exercise testing. *Anaesthesia*, 66(2), 111-123.
- Mader, A., Heck, H., & Hollman, W. (1978). Evaluation of lactic acid anaerobic energy contribution by determination of post exercise lactic acid concentration of ear capillary blood in middle-distance runners and swimmers. In F. Landry & W. Orban (Eds.), *Exercise Physiology. Symposia Specialists* (pp. 187-200). Miami.
- McLellan, T. M., & Cheung, K. S. Y. (1992). A comparative-evaluation of the individual anaerobic threshold and the critical power. *Medicine and Science in Sports and Exercise*, 24(5), 543-550.
- Meyer, T., Lucia, A., Earnest, C. P., & Kindermann, W. (2005). A conceptual framework for performance diagnosis and training prescription from submaximal gas exchange parameters - Theory and application. *International Journal of Sports Medicine*, 26(suppl 1), S38-S48.
- Michele, R. D., Gatta, G., Leo, A. D., Cortesi, M., Andina, F., Tam, E., Boit, M. D., & Merni, F. (2011). Estimation of the anaerobic threshold from heart rate variability in an

- incremental swimming test. *The Journal of Strength & Conditioning Research*.
- Pluto, R., Cruze, S. A., Weiss, M., Hotz, T., Mandel, P., & Weicker, H. (1988). Cardiocirculatory, hormonal, and metabolic reactions to various forms of ergometric tests. *International Journal of Sports Medicine*, 9(Suppl. 2), S79-S88.
- Robergs, R. A., Ghiasvand, F., & Parker, D. (2004). Biochemistry of exercise-induced metabolic acidosis. *American Journal of Physiology - Regulatory Integrative and Comparative Physiology*, 287(3 56-3), R502-R516.
- Roels, B., Schmitt, L., Libicz, S., Bentley, D., Richalet, J. P., & Millet, G. (2005). Specificity of $\text{VO}_{2\text{max}}$ and the ventilatory threshold in free swimming and cycle ergometry: Comparison between triathletes and swimmers. *British Journal of Sports Medicine*, 39(12), 965-968.
- Smith, B. W., McMurray, R. G., & Symanski, J. D. (1984). A comparison of the anaerobic threshold of sprint and endurance trained swimmers. *Journal of Sports Medicine and Physical Fitness*, 24(2), 94-99.
- Sousa, A. C., Figueiredo, P., Oliveira, N. L., Oliveira, J., Silva, A. J., Keskinen, K. L., Rodriguez, F. A., MacHado, L. J., Vilas-Boas, J. P., & Fernandes, R. J. (2011). VO_2 kinetics in 200-m race-pace front crawl swimming. *International Journal of Sports Medicine*, 32(10), 765-770.
- Stegmann, H., & Kindermann, W. (1982). Comparison of prolonged exercise tests at the individual anaerobic threshold and the fixed anaerobic threshold of 4 mmol-1 lactate. *International Journal of Sports Medicine*, 3(2), 105-110.
- Stenberg, J., Astrand, P. O., Ekblom, B., Royce, J., & Saltin, B. (1967). Hemodynamic response to work with different muscle groups, sitting and supine. *Journal of Applied Physiology*, 22(1), 61-70.
- Svedahl, K., & MacIntosh, B. R. (2003). Anaerobic threshold: The concept and methods of measurement. *Canadian Journal of Applied Physiology*, 28(2), 299-323.
- Ward, S. A. (2000). Control of the exercise hyperpnoea in humans: A modeling perspective. *Respiration Physiology*, 122(2-3), 149-166.
- Wasserman, K., Whipp, B. J., Koyal, S. N., & Beaver, W. L. (1973). Anaerobic threshold and respiratory gas exchange during exercise. *Journal of Applied Physiology*, 35(2), 236-243.

Chapter 5

- Baldari, C., Fernandes, R. J., Meucci, M., Ribeiro, J., Vilas-Boas, J. P., & Guidetti, L. (2013). Is the new AquaTrainer® snorkel valid for VO_2 assessment in swimming? *International Journal of Sports Medicine*, 34(4), 336-344.
- Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010). Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. *Journal of Science and Medicine in Sport*, 13(2), 262-269.
- Chollet, D., Challes, S., & Chatard, J. C. (2000). A new index of coordination for the crawl: Description and usefulness. *International Journal of Sports Medicine*, 21(1), 54-59.
- Craig, A. B., Skehan, P. L., Pawelczyk, J. A., & Boomer, W. L. (1985). Velocity, stroke rate, and distance per stroke during elite swimming competition. *Medicine and Science in Sports and Exercise*, 17(6), 625-634.
- De Jesus, K., De Jesus, K., Figueiredo, P., Vilas-Boas, J. P., Fernandes, R. J., & Machado, L. J. (2015). Reconstruction Accuracy Assessment of Surface and Underwater 3D Motion Analysis: A New Approach. *Computational and Mathematical Methods in Medicine*, 2015.
- De Koning, J. J., Noordhof, D. A., Lucia, A., & Foster, C. (2012). Factors affecting gross efficiency in cycling. *International Journal of Sports Medicine*, 33(11), 880-885.
- De Leva, P. (1996). Adjustments to zatsiorsky-seluyanov's segment inertia parameters. *Journal of Biomechanics*, 29(9), 1223-1230.
- di Prampero, P. E., Pendergast, D., Wilson, D., & Rennie, D. W. (1978). Blood lactic acid concentrations in high velocity swimming. In B. Eriksson & B. Furberg (Eds.), *Swimming medicine IV* (pp. 249-261). Baltimore: University Park Press.
- Ettema, G., & Lorås, H. W. (2009). Efficiency in cycling: A review. *European Journal of Applied*

- Physiology*, 106(1), 1-14.
- Fernandes, R. J., Billat, V. L., Cruz, A. C., Colaço, P. J., Cardoso, C. S., & Vilas-Boas, J. P. (2006). Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity? *Journal of Sports Medicine and Physical Fitness*, 46(3), 373-380.
- Fernandes, R. J., De Jesus, K., Baldari, C., De Jesus, K., Sousa, A. C., Vilas-Boas, J. P., & Guidetti, L. (2012). Different $\text{VO}_{2\text{max}}$ time-averaging intervals in swimming. *International Journal of Sports Medicine*, 33(12), 1010-1015.
- Fernandes, R. J., Keskinen, K. L., Colaço, P., Querido, A. J., Machado, L. J., Morais, P. A., Novais, D. Q., Marinho, D. A., & Vilas Boas, J. P. (2008). Time limit at $\text{VO}_{2\text{max}}$ velocity in elite crawl swimmers. *International Journal of Sports Medicine*, 29(2), 145-150.
- Fernandes, R. J., Sousa, M., MacHado, L., & Vilas-Boas, J. P. (2011). Step length and individual anaerobic threshold assessment in swimming. *International Journal of Sports Medicine*, 32(12), 940-946.
- Figueiredo, P., Morais, P., Vilas-Boas, J. P., & Fernandes, R. J. (2013). Changes in arm coordination and stroke parameters on transition through the lactate threshold. *European Journal of Applied Physiology*, 113(8), 1957-1964.
- Figueiredo, P., Nazario, R., Sousa, M., Pelarigo, J. G., Vilas-Boas, J. P., & Fernandes, R. (2014). Kinematical analysis along maximal lactate steady state swimming intensity. *Journal of Sports Science and Medicine*, 13(3), 610-615.
- Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J. P., & Fernandes, R. J. (2011). An energy balance of the 200 m front crawl race. *European Journal of Applied Physiology*, 111(5), 767-777.
- Glazier, P. S., Wheat, J. S., Pease, D., & Bartlett, R. M. (2006). Dynamic systems theory and the functional role of movement variability. In K. Davids, S. J. Bennett & K. Newell (Eds.), *Movement system variability*. Champaign, IL: Human Kinetics Publishers.
- Gourgoulis, V., Boli, A., Aggeloussis, N., Antoniou, P., Toubekis, A., & Mavromatis, G. (2015). The influence of the hand's acceleration and the relative contribution of drag and lift forces in front crawl swimming. *Journal of Sports Sciences*, 33(7), 696-712.
- Hawley, J. A., Williams, M. M., Vickovic, M. M., & Handcock, P. J. (1992). Muscle power predicts freestyle swimming performance. *British Journal of Sports Medicine*, 26(3), 151-155.
- Keskinen, K., & Komi, P. V. (1993). Stroking characteristics of front crawl swimming during exercise. *Journal of Applied Biomechanics*, 9(3), 219-226.
- Kolmogorov, S. V., & Duplishcheva, O. A. (1992). Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. *Journal of Biomechanics*, 25(3), 311-318.
- Kolmogorov, S. V., Vorontsov, A. R., Rummyantseva, O. A., & Kochergin, A. B. (2010). Mechanical and Propulsive Efficiency of Swimmers in Different Zones of Energy Supply. In P. L. Kjendlie, R. K. Stallman & J. Cabri (Eds.), *Xlth International Symposium for Biomechanics and Medicine in Swimming* (pp. 110-112). Oslo: Norwegian School of Sport Science.
- Kuipers, H., Verstappen, F. T. J., Keizer, H. A., Geurten, P., & van Kranenburg, G. (1985). Variability of aerobic performance in the laboratory and its physiologic correlates. *International Journal of Sports Medicine*, 6(4), 197-201.
- Maglischo, E. W. (2003). *Swimming fastest: The essential reference on technique, training, and program design*. Champaign, IL: Human Kinetics Publisher.
- Olbrecht, J. (2000). *The science of winning. Planning, periodizing and optimizing swim training*. Luton: Swimshop.
- Pendergast, D. R., Capelli, C., Craig, A., Di Prampero, P. E., Minetti, A. E., Mollendorf, J., Termin, A., & Zamparo, P. (2006). Biophysics in swimming. In J. P. Vilas-Boas, F. Alves & A. Marques (Eds.), *Xth International Symposium of Biomechanics and Medicine in Swimming* (pp. 185-189). Porto, Portugal.
- Pendergast, D. R., Di Prampero, P. E., Craig, A. B., Jr., Wilson, D. R., & Rennie, D. W. (1977). Quantitative analysis of the front crawl in men and women. *Journal of Applied Physiology*, 43(3), 475-479.
- Pessôa Filho, D. M., Greco, C. C., & Denadai, B. S. (2014). Tether-power at maximal lactate steady-state and endurance indexes of swimming performance. *Brazilian Journal of*

- Sports Medicine*, 20(5), 359-365.
- Poole, D. C., Wilkerson, D. P., & Jones, A. M. (2008). Validity of criteria for establishing maximal O₂ uptake during ramp exercise tests. *European Journal of Applied Physiology*, 102(4), 403-410.
- Potdevin, F., Bril, B., Sidney, M., & Pelayo, P. (2006). Stroke frequency and arm coordination in front crawl swimming. *International Journal of Sports Medicine*, 27(3), 193-198.
- Psycharakis, S. G., Cooke, C. B., Paradisis, G. P., O'Hara, J., & Phillips, G. (2008). Analysis of selected kinematic and physiological performance determinants during incremental testing in elite swimmers. *Journal of Strength and Conditioning Research*, 22(3), 951-957.
- Pyne, D. B., Lee, H., & Swanwick, K. M. (2001). Monitoring the lactate threshold in world-ranked swimmers. *Medicine and Science in Sports and Exercise*, 33(2), 291-297.
- Ribeiro, J., De Jesus, K., Figueiredo, P., Toussaint, H., Guidetti, L., Alves, F., Vilas-Boas, J., & Fernandes, R. (2013). Biomechanical determinants of force production in front crawl swimming. *Journal of Sports Medicine and Physical Fitness* 53(3 suppl 1), 30-37.
- Ribeiro, J., Figueiredo, P., Guidetti, L., Alves, F., Toussaint, H., Vilas-Boas, J. P., Baldari, C., & Fernandes, R. J. (2015). AquaTrainer® snorkel does not increase hydrodynamic drag but influences turning time. *International Journal of Sports Medicine*, (in press).
- Seifert, L., Chollet, D., & Bardy, B. G. (2004). Effect of swimming velocity on arm coordination in the front crawl: A dynamic analysis. *Journal of Sports Sciences*, 22(7), 651-660.
- Seifert, L., Chollet, D., & Rouard, A. (2007). Swimming constraints and arm coordination. *Human Movement Science*, 26(1), 68-86.
- Seifert, L., Schnitzler, C., Bideault, G., Alberty, M., Chollet, D., & Toussaint, H. M. (2015). Relationships between coordination, active drag and propelling efficiency in crawl. *Human Movement Science*, 39, 55-64.
- Sharp, R. L., Troup, J. P., & Costill, D. L. (1982). Relationship between power and sprint freestyle swimming. *Medicine and Science in Sports and Exercise*, 14(1), 53-56.
- Swaine, I. (1994). The relationship between physiological variables from a swim bench ramp test and middle-distance swimming performance. *Journal of Swimming Research*, 10, 41-48.
- Tomikawa, M., & Nomura, T. (2009). Relationships between swim performance, maximal oxygen uptake and peak power output when wearing a wetsuit. *Journal of Science and Medicine in Sport*, 12(2), 317-322.
- Toussaint, H., & Beek, P. (1992). Biomechanics of competitive front crawl swimming. *Sports Medicine*, 13 (1), 8-24.
- Toussaint, H. M., de Groot, G., Savelberg, H. H. C. M., Vervoorn, K., Hollander, A. P., & Van Ingen Schenau, G. J. (1988). Active drag related to velocity in male and female swimmers. *Journal of Biomechanics*, 21(5), 435-438.
- Toussaint, H. M., & Hollander, A. P. (1994). Energetics of competitive swimming: Implications for training programmes. *Sports Medicine*, 18(6), 384-405.
- Toussaint, H. M., Knops, W., De Groot, G., & Hollander, A. P. (1990). The mechanical efficiency of front crawl swimming. *Medicine and Science in Sports and Exercise*, 22(3), 402-408.
- Toussaint, H. M., Meulemans, A., de Groot, G., Hollander, A. P., Schreurs, A. W., & Vervoorn, K. (1987). Respiratory valve for oxygen uptake measurements during swimming. *European Journal of Applied Physiology* 56(3), 363-366.
- Toussaint, H. M., Roos, P. E., & Kolmogorov, S. (2004). The determination of drag in front crawl swimming. *Journal of Biomechanics*, 37(11), 1655-1663.
- Toussaint, H. M., & Vervoorn, K. (1990). Effects of specific high resistance training in the water on competitive swimmers. *International Journal of Sports Medicine*, 11(3), 228-233.
- Triantafyllou, M. S., & Triantafyllou, G. S. (1995). An efficient swimming machine. *Scientific American*, 272(3), 40-48.
- Zamparo, P. (2006). Effects of age and gender on the propelling efficiency of the arm stroke. *European Journal of Applied Physiology*, 97(1), 52-58.
- Zamparo, P., Lazzer, S., Antoniazzi, C., Cedolin, S., Avon, R., & Lesa, C. (2008). The interplay between propelling efficiency, hydrodynamic position and energy cost of front crawl in 8 to 19-year-old swimmers. *European Journal of Applied Physiology*, 104(4), 689-699.
- Zamparo, P., Pendergast, D. R., Mollendorf, J., Termin, A., & Minetti, A. E. (2005). An energy balance of front crawl. *European Journal of Applied Physiology*, 94(1-2), 134-144.

Zamparo, P., & Swaine, I. L. (2012). Mechanical and propelling efficiency in swimming derived from exercise using a laboratory-based whole-body swimming ergometer. *Journal of Applied Physiology*, 113(4), 584-594.

Chapter 6

- Alberty, M., Potdevin, F., Dekerle, J., Pelayo, P., Gorce, P., & Sidney, M. (2008). Changes in swimming technique during time to exhaustion at freely chosen and controlled stroke rates. *Journal of Sports Sciences*, 26(11), 1191-1200.
- Alberty, M., Sidney, M., Huot-Marchand, F., Hespel, J. M., & Pelayo, P. (2005). Intracyclic velocity variations and arm coordination during exhaustive exercise in front crawl stroke. *International Journal of Sports Medicine*, 26(6), 471-475.
- Ajouannet, Y. A., Bonifazi, M., Hintzy, F., Vuillerme, N., & Rouard, A. H. (2006). Effects of a high-intensity swim test on kinematic parameters in high-level athletes. *Applied Physiology, Nutrition and Metabolism*, 31(2), 150-158.
- Berger, M. A. M., de Groot, G., & Hollander, A. P. (1995). Hydrodynamic drag and lift forces on human hand/arm models. *Journal of Biomechanics*, 28(2), 125-133.
- Bonifazi, M., Martelli, G., Marugo, L., Sardella, F., & Carli, G. (1993). Blood lactate accumulation in top level swimmers following competition. *J Sports Med Phys Fitness*, 33(1), 13-18.
- Chollet, D., Chabies, S., & Chatard, J. C. (2000). A new index of coordination for the crawl: Description and usefulness. *International Journal of Sports Medicine*, 21(1), 54-59.
- Chollet, D., Delaplace, C., Pelayo, P., Tourny, C., & Sidney, M. (1997). Stroking characteristic variations in the 100-M freestyle for male swimmers of differing skill. *Perceptual and Motor Skills*, 85(1), 167-177.
- Craig, A. B., Skehan, P. L., Pawelczyk, J. A., & Boomer, W. L. (1985). Velocity, stroke rate, and distance per stroke during elite swimming competition. *Medicine & Science in Sports & Exercise*, 17(6), 625-634.
- Deschodt, J. V., Arsac, L. M., & Rouard, A. H. (1999). Relative contribution of arms and legs in humans to propulsion in 25-m sprint front-crawl swimming. *European Journal of Applied Physiology and Occupational Physiology*, 80(3), 192-199.
- Figueiredo, P., Sanders, R., Gorski, T., Vilas-Boas, J. P., & Fernandes, R. J. (2013). Kinematic and electromyographic changes during 200 m front crawl at race pace. *International Journal of Sports Medicine*, 34(1), 49-55.
- Fitts, R. H. (1994). Cellular mechanisms of muscle fatigue. *Physiological reviews*, 74(1), 49-94.
- Goldfuss, A. J. N., R. C. (1971). A temporal and force analysis of the crawl arm stroke during tethered swimming. In L. L. a. J. P. Clarys (Ed.), *First International Symposium on Biomechanics in Swimming Proceedings*. Brussels: Université Libre de Bruxelles.
- Keskinen, K., & Komi, P. V. (1993). Stroking characteristics of front crawl swimming during exercise. *Journal of Applied Biomechanics*, 9(3), 219-226.
- Seifert, L., Boulesteix, L., Carter, M., & Chollet, D. (2005). The spatial-temporal and coordinative structures in elite male 100-m front crawl swimmers. *International Journal of Sports Medicine*, 26(4), 286-293.
- Suito, H., Ikegami, Y., Nunome, H., Sano, S., Shinkai, H., & Tsujimoto, N. (2008). The effect of fatigue on the underwater arm stroke motion in the 100-m front crawl. *Journal of Applied Biomechanics*, 24(4), 316-324.
- Toussaint, H. M., Carol, A., Kranenborg, H., & Truijens, M. J. (2006). Effect of fatigue on stroking characteristics in an arms-only 100-m front-crawl race. *Medicine and Science in Sports and Exercise*, 38(9), 1635-1642.
- Vorontsov, A. R., & Binevsky, D. A. (2003). Swimming Speed, Stroke Rate and Stroke Length During Maximal 100 m Freestyle of Boys 11-16 Years of Age. In J. C. Chatard. (Ed.), *Biomechanics and Medicine in Swimming IX* (pp. 195-201). Saint-Étienne: Publications de l'Université de Saint-Étienne.

Chapter 7

- Bailey, S. J., Vanhatalo, A., Wilkerson, D. P., Dimenna, F. J., & Jones, A. M. (2009). Optimizing the "priming" effect: Influence of prior exercise intensity and recovery duration on O₂ uptake kinetics and severe-intensity exercise tolerance. *Journal of Applied Physiology*, 107(6), 1743-1756.
- Baldari, C., Fernandes, R. J., Meucci, M., Ribeiro, J., Vilas-Boas, J. P., & Guidetti, L. (2013). Is the new AquaTrainer® snorkel valid for VO₂ assessment in swimming? *International Journal of Sports Medicine*, 34(4), 336-344.
- Binzoni, T., Ferretti, G., Schenker, K., & Cerretelli, P. (1992). Phosphocreatine hydrolysis by ³¹P-NMR at the onset of constant-load exercise in humans. *Journal of Applied Physiology*, 73(4), 1644-1649.
- Burnley, M., & Jones, A. M. (2007). Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sport Science*, 7(2), 63-79.
- Capelli, C., Pendergast, D. R., & Termin, B. (1998). Energetics of swimming at maximal speeds in humans. *European Journal of Applied Physiology and Occupational Physiology*, 78(5), 385-393.
- de Jesus, K., Guidetti, L., de Jesus, K., Vilas-Boas, J. P., Baldari, C., & Fernandes, R. J. (2014). Which are the best VO₂ sampling Intervals to characterize low to severe swimming intensities? *International Journal of Sports Medicine*, DOI: 10.1055/s-0034-1368784.
- di Prampero, P. E., Pendergast, D., Wilson, D., & Rennie, D. W. (1978). Blood lactic acid concentrations in high velocity swimming. In B. Eriksson & B. Furberg (Eds.), *Swimming medicine IV* (pp. 249-261). Baltimore: University Park Press.
- Fernandes, R. J., Billat, V. L., Cruz, A. C., Colaço, P. J., Cardoso, C. S., & Vilas-Boas, J. P. (2006). Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity? *Journal of Sports Medicine and Physical Fitness*, 46(3), 373-380.
- Fernandes, R. J., & Vilas-Boas, J. P. (2012). Time to exhaustion at the VO_{2max} velocity in swimming: A review. *Journal of Human Kinetics*, 32(1), 121-134.
- Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J. P., & Fernandes, R. J. (2011). An energy balance of the 200 m front crawl race. *European Journal of Applied Physiology*, 111(5), 767-777.
- Gatta, G., Cortesi, M., & Di Michele, R. (2012). Power production of the lower limbs in flutter-kick swimming. *Sports Biomechanics*, 11(4), 480-491.
- Gourgoulis, V., Boli, A., Aggeloussis, N., Toubekis, A., Antoniou, P., Kasimatis, P., Vezos, N., Michalopoulou, M., Kambas, A., & Mavromatis, G. (2014). The effect of leg kick on sprint front crawl swimming. *Journal of Sports Sciences*, 32(3), 278-289.
- Holmer, I. (1974). Energy cost of arm stroke, leg kick, and the whole stroke in competitive swimming styles. *European Journal of Applied Physiology and Occupational Physiology*, 33(2), 105-118.
- Jones, A. M., Wilkerson, D. P., Vanhatalo, A., & Burnley, M. (2008). Influence of pacing strategy on O₂ uptake and exercise tolerance. *Scandinavian Journal of Medicine and Science in Sports*, 18(5), 615-626.
- Koga, S., Shiojiri, T., Shibasaki, M., Fukuba, Y., Fukuoka, Y., & Kondo, N. (1996). Kinetics of oxygen uptake and cardiac output at onset of arm exercise. *Respiration Physiology*, 103(2), 195-202.
- Markovitz, G. H., Sayre, J. W., Storer, T. W., & Cooper, C. B. (2004). On issues of confidence in determining the time constant for oxygen uptake kinetics. *British Journal of Sports Medicine*, 38(5), 553-560.
- Medbo, J. I. (1996). Is the Maximal Accumulated Oxygen Deficit an Adequate Measure of the Anaerobic Capacity? *Canadian Journal of Applied Physiology*, 21(5), 370-383.
- Ogita, F. (2006). Energetics in competitive swimming and its application for training. *Portuguese Journal of Sports Science* 6, 117-121.
- Ogita, F., Hara, M., & Tabata, I. (1996). Anaerobic capacity and maximal oxygen uptake during arm stroke, leg kicking and whole body swimming. *Acta Physiologica Scandinavica*, 157(4), 435-441.
- Ogita, F., Onodera, T., Tamaki, H., Toussaint, H., Hollander, P., & Wakayoshi, K. (2003). Metabolic Profile During Exhaustive Arm Stroke, Leg Kick and Whole Body Swimming

- Lasting 15 s to 10 min. In J. C. Chatard (Ed.), *Biomechanics and Medicine in Swimming IX* (pp. 361-367). Saint-Étienne: Publications de l'Université de Saint-Étienne.
- Olbrecht, J. (2000). *The science of winning. Planning, periodizing and optimizing swim training*. Luton: Swimshop.
- Pendergast, D. R. (1989). Cardiovascular, respiratory, and metabolic responses to upper body exercise. *Medicine and Science in Sports and Exercise*, 21(5 SUPPL.), S121-S125.
- Pessoa Filho, D. M., Alves, F. B., Reis, J. F., Greco, C. C., & Denadai, B. S. (2012). VO₂ kinetics during heavy and severe exercise in swimming. *International Journal of Sports Medicine*, 33(9), 744-748.
- Peyrebrune, M. C., Toubekis, A. G., Lakomy, H. K. A., & Nevill, M. E. (2014). Estimating the energy contribution during single and repeated sprint swimming. *Scandinavian Journal of Medicine and Science in Sports*, 24(2), 369-376.
- Reis, J. F., Alves, F. B., Bruno, P. M., Vleck, V., & Millet, G. P. (2012a). Effects of aerobic fitness on oxygen uptake kinetics in heavy intensity swimming. *European Journal of Applied Physiology*, 112(5), 1689-1697.
- Reis, J. F., Alves, F. B., Bruno, P. M., Vleck, V., & Millet, G. P. (2012b). Oxygen uptake kinetics and middle distance swimming performance. *Journal of Science and Medicine in Sport*, 15(1), 58-63.
- Reis, V. M., Marinho, D. A., Policarpo, F. B., Carneiro, A. L., Baldari, C., & Silva, A. J. (2010). Examining the accumulated oxygen deficit method in front crawl swimming. *International Journal of Sports Medicine*, 31(6), 421-427.
- Reis, V. M., Santos, E. L., Oliveira, D. R., Gonçalves, L. F., Carneiro, A. L., & Fernandes, R. J. (2013). Oxygen uptake slow component at submaximal swimming. *Gazzetta Medica Italiana Archivio per le Scienze Mediche*, 172(7-8), 603-610.
- Ribeiro, J., Baldari, C., Guidetti, L., Figueiredo, P., Toussaint, H., Vilas-Boas, J. P., & Fernandes, R. J. (2011). Drag assessment in front crawl swimming while using Aquatrainer Snorkel. *Journal of Sports Medicine and Physical Fitness* 51, 12.
- Rodriguez, F. A., Keskinen, K. L., Keskinen, O. P., & Malvela, M. (2003). Oxygen Uptake Kinetics During Free Swimming: A Pilot Study. In J. C. Chatard (Ed.), *Biomechanics and Medicine in Swimming IX* (pp. 379-385). Saint-Étienne: Publications de l'Université de Saint-Étienne.
- Sahlin, K., & Henriksson, J. (1984). Buffer capacity and lactate accumulation in skeletal muscle of trained and untrained men. *Acta Physiologica Scandinavica*, 122(3), 331-339.
- Secher, N. H., & Volianitis, S. (2006). Are the arms and legs in competition for cardiac output? *Medicine and Science in Sports and Exercise*, 38(10), 1797-1803.
- Sousa, A., Figueiredo, P., Oliveira, N., Oliveira, J., Silva, A., Keskinen, K., Rodriguez, F., Machado, L., Vilas-Boas, J., & Fernandes, R. (2011). VO₂ kinetics in 200-m race-pace front crawl swimming. *International Journal of Sports Medicine*, 32(10), 765-770.
- Sousa, A., Figueiredo, P., Zamparo, P., Vilas-Boas, J. P., & Fernandes, R. J. (2013). Anaerobic alactic energy assessment in middle distance swimming. *European Journal of Applied Physiology*, 113(8), 2153-2158.
- Sousa, A., Vilas Boas, J. P., & Fernandes, R. J. (2014). VO₂ Kinetics and Metabolic Contributions Whilst Swimming at 95, 100, and 105% of the Velocity at VO_{2max}. *BioMed Research International*, doi: 10.1155/2014/675363.
- Toussaint, H. (2011). Biomechanics of drag and propulsion in front crawl swimming. In L. Seifert, D. Chollet & I. Mujika (Eds.), *World book of swimming: From science to performance* (pp. 3-20). New York: Nova Science Publishers, Inc.
- Toussaint, H. M., Beelen, A., Rodenburg, A., Sargeant, A. J., De Groot, G., Hollander, A. P., & Van Ingen Schenau, G. J. (1988). Propelling efficiency of front-crawl swimming. *Journal of Applied Physiology*, 65(6), 2506-2512.
- Toussaint, H. M., Hollander, A. P., de Groot, G., Kahman, R., & van Ingen Schenau, G. J. (1990a). Power of leg kicking in front crawl swimming. In N. Berme & A. Capozzo (Eds.), *Biomechanics of human movement* (pp. 456-459). Worthington: Bertec Corporation.
- Toussaint, H. M., Knops, W., De Groot, G., & Hollander, A. P. (1990b). The mechanical efficiency of front crawl swimming. *Medicine and Science in Sports and Exercise*, 22(3), 402-408.
- Troup, J. P. (1991). Aerobic: Anaerobic characteristics of the four competitive strokes. In J. P.

- Troup (Ed.), *International center for aquatic research annual. Studies by the international center for aquatic research (1990–1991)* (pp. 3-7). Colorado Springs: US Swimming Press.
- Wakayoshi, K., D'Acquisto, L. J., Cappaert, J. M., & Troup, J. P. (1995). Relationship between oxygen uptake, stroke rate and swimming velocity in competitive swimming. *International Journal of Sports Medicine*, 16(1), 19-23.
- Zamparo, P., Capelli, C., Cautero, M., & Di Nino, A. (2000). Energy cost of front-crawl swimming at supra-maximal speeds and underwater torque in young swimmers. *European Journal of Applied Physiology*, 83(6), 487-491.
- Zamparo, P., Capelli, C., & Pendergast, D. (2011). Energetics of swimming: A historical perspective. *European Journal of Applied Physiology*, 111(3), 367-378.
- Zhang, Y. Y., Johnson, M. C., 2nd, Chow, N., & Wasserman, K. (1991). The role of fitness on VO_2 and VCO_2 kinetics in response to proportional step increases in work rate. *European Journal of Applied Physiology* 63(2), 94-100.

Chapter 8

- Alberty, M., Sidney, M., Huot-Marchand, F., Hespel, J. M., & Pelayo, P. (2005). Intracyclic velocity variations and arm coordination during exhaustive exercise in front crawl stroke. *International Journal of Sports Medicine*, 26(6), 471-475.
- Bailey, S. J., Vanhatalo, A., Wilkerson, D. P., Dimenna, F. J., & Jones, A. M. (2009). Optimizing the "priming" effect: Influence of prior exercise intensity and recovery duration on O_2 uptake kinetics and severe-intensity exercise tolerance. *Journal of Applied Physiology*, 107(6), 1743-1756.
- Baldari, C., Fernandes, R. J., Meucci, M., Ribeiro, J., Vilas-Boas, J. P., & Guidetti, L. (2013). Is the new AquaTrainer® snorkel valid for VO_2 assessment in swimming? *International Journal of Sports Medicine*, 34(4), 336-344.
- Bideault, G., Herault, R., & Seifert, L. (2013). Data modelling reveals inter-individual variability of front crawl swimming. *Journal of Science and Medicine in Sport*, 16(3), 281-285.
- Binzoni, T., Ferretti, G., Schenker, K., & Cerretelli, P. (1992). Phosphocreatine hydrolysis by ^{31}P -NMR at the onset of constant-load exercise in humans. *Journal of Applied Physiology*, 73(4), 1644-1649.
- Capelli, C., Pendergast, D. R., & Termin, B. (1998). Energetics of swimming at maximal speeds in humans. *European Journal of Applied Physiology and Occupational Physiology*, 78(5), 385-393.
- Cappaert, J. M., Bone, M., & Troup, J. P. (1992). Intensity and performance related differences in propelling and mechanical efficiencies. In D. Maclaren, T. Reilly & A. Lees (Eds.), *Biomechanics and Medicine in Swimming, Swimming Science VI* (pp. 49-52). London: E & FN Spon.
- Chollet, D., Chabies, S., & Chatard, J. C. (2000). A new index of coordination for the crawl: Description and usefulness. *International Journal of Sports Medicine*, 21(1), 54-59.
- Chollet, D., Delaplace, C., Pelayo, P., Tourny, C., & Sidney, M. (1997). Stroking characteristic variations in the 100-M freestyle for male swimmers of differing skill. *Perceptual and Motor Skills*, 85(1), 167-177.
- Clarys, J. P., Toussaint, H. M., Bollens, E., Vaes, W., Huijing, P. A., De Groot, G., Hollander, A. P., De Witte, B., & Cabri, J. (1988). Muscular specificity and intensity in swimming against a mechanical resistance - surface EMG in MAD and free swimming. In B. E. Ungerechts, K. Wilkie & K. Reischle (Eds.), *Swimming Science V* (pp. 191-199). Champaign, Illinois: Human Kinetics Publishers.
- Craig, A. B., Skehan, P. L., Pawelczyk, J. A., & Boomer, W. L. (1985). Velocity, stroke rate, and distance per stroke during elite swimming competition. *Medicine and Science in Sports and Exercise*, 17(6), 625-634.
- Davids, K., Button, C., & Bennett, S. J. (2008). *Dynamics of skill acquisition: a constraints-led approach*. Champaign, IL: Human Kinetics Publishers.
- di Prampero, P. E., Pendergast, D., Wilson, D., & Rennie, D. W. (1978). Blood lactic acid concentrations in high velocity swimming. In B. Eriksson & B. Furberg (Eds.), *Swimming*

- medicine IV* (pp. 249–261). Baltimore: University Park Press.
- Fernandes, R. J., Billat, V. L., Cruz, A. C., Colaço, P. J., Cardoso, C. S., & Vilas-Boas, J. P. (2006). Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity? *Journal of Sports Medicine and Physical Fitness*, 46(3), 373-380.
- Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J. P., & Fernandes, R. J. (2011). An energy balance of the 200 m front crawl race. *European Journal of Applied Physiology*, 111(5), 767-777.
- Glazier, P. S., Wheat, J. S., Pease, D., & Bartlett, R. M. (2006). Dynamic systems theory and the functional role of movement variability. In K. Davids, S. J. Bennett & K. Newell (Eds.), *Movement system variability*. Champaign, IL: Human Kinetics Publishers.
- Hawley, J. A., & Williams, M. M. (1991). Relationship between upper body anaerobic power and freestyle swimming performance. *International Journal of Sports Medicine*, 12(1), 1-5.
- Hawley, J. A., Williams, M. M., Vickovic, M. M., & Handcock, P. J. (1992). Muscle power predicts freestyle swimming performance. *British Journal of Sports Medicine*, 26(3), 151-155.
- Hollander, A. P., De Groot, G., Van Ingen Schenau, G. J., Kahman, R., & Toussaint, H. M. (1988). Contribution of the legs to propulsion in swimming. In B. E. Ungerechts, K. Wilkie & K. Reischle (Eds.), *Swimming Science V* (pp. 39-43). Champaign, Illinois: Human Kinetics Publishers.
- Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, 41(1), 3-12.
- Lätt, E., Jürimäe, J., Mäestu, J., Purge, P., Rämson, R., Haljaste, K., Keskinen, K. L., Rodriguez, F. A., & Jürimäe, T. (2010). Physiological, biomechanical and anthropometrical predictors of sprint swimming performance in adolescent swimmers. *Journal of Sports Science and Medicine*, 9(3), 398-404.
- Lerda, R., & Cardelli, C. (2003). Breathing and propelling in crawl as a function of skill and swim velocity. *International Journal of Sports Medicine*, 24(1), 75-80.
- Maglischo, E. W. (2003). *Swimming fastest: The essential reference on technique, training, and program design*. Champaign, IL: Human Kinetics Publisher.
- Ribeiro, J., De Jesus, K., Figueiredo, P., Toussaint, H., Guidetti, L., Alves, F., Vilas-Boas, J., & Fernandes, R. (2013). Biomechanical determinants of force production in front crawl swimming. *Journal of Sports Medicine and Physical Fitness* 53(3 suppl 1), 30-37.
- Ribeiro, J., Figueiredo, P., Guidetti, L., Alves, F., Toussaint, H., Vilas-Boas, J. P., Baldari, C., & Fernandes, R. J. (2015a). AquaTrainer® snorkel does not increase hydrodynamic drag but influences turning time. *International Journal of Sports Medicine*, (in press).
- Ribeiro, J., Figueiredo, P., Sousa, A., Monteiro, J., Pelarigo, J., Vilas-Boas, J. P., Toussaint, H. M., & Fernandes, R. F. (2015b). VO₂ kinetics and metabolic contributions during full and upper body extreme swimming intensity. *European Journal of Applied Physiology*, 115, 1117-1124.
- Seifert, L., Boulesteix, L., Carter, M., & Chollet, D. (2005). The spatial-temporal and coordinative structures in elite male 100-m front crawl swimmers. *International Journal of Sports Medicine*, 26(4), 286-293.
- Seifert, L., Chollet, D., & Chatard, J. C. (2007). Kinematic changes during a 100-m front crawl: Effects of performance level and gender. *Medicine and Science in Sports and Exercise*, 39(10), 1784-1793.
- Seifert, L., Komar, J., Barbosa, T., Toussaint, H., Millet, G., & Davids, K. (2014). Coordination Pattern Variability Provides Functional Adaptations to Constraints in Swimming Performance. *Sports Medicine*.
- Seifert, L., Komar, J., Lepitre, P. M., Lemaitre, F., Chavallard, F., Alberty, M., Houel, N., Hausswirth, C., Chollet, D., & Hellard, P. (2010b). Swim specialty affects energy cost and motor organization. *International Journal of Sports Medicine*, 31(9), 624-630.
- Seifert, L., Schnitzler, C., Bideault, G., Alberty, M., Chollet, D., & Toussaint, H. M. (2015). Relationships between coordination, active drag and propelling efficiency in crawl. *Human Movement Science*, 39, 55-64.
- Seifert, L., Toussaint, H. M., Alberty, M., Schnitzler, C., & Chollet, D. (2010a). Arm coordination, power, and swim efficiency in national and regional front crawl swimmers. *Human*

- Movement Science*, 29(3), 426-439.
- Sharp, R. L., Troup, J. P., & Costill, D. L. (1982). Relationship between power and sprint freestyle swimming. *Medicine and Science in Sports and Exercise*, 14(1), 53-56.
- Sousa, A., Vilas Boas, J. P., & Fernandes, R. J. (2014). VO₂ Kinetics and Metabolic Contributions Whilst Swimming at 95, 100, and 105% of the Velocity at VO_{2max}. *BioMed Research International*, doi: 10.1155/2014/675363.
- Toussaint, H. M., Carol, A., Kranenborg, H., & Truijens, M. J. (2006). Effect of fatigue on stroking characteristics in an arms-only 100-m front-crawl race. *Medicine and Science in Sports and Exercise*, 38(9), 1635-1642.
- Toussaint, H. M., & Hollander, A. P. (1994). Energetics of competitive swimming: Implications for training programmes. *Sports Medicine*, 18(6), 384-405.
- Toussaint, H. M., Van Den Berg, C., & Beek, W. J. (2002). "Pumped-up propulsion" during front crawl swimming. *Medicine and Science in Sports and Exercise*, 34(2), 314-319.
- Triantafyllou, M. S., & Triantafyllou, G. S. (1995). An efficient swimming machine. *Scientific American*, 272(3), 40-48.
- Vorontsov, A. R., & Binevsky, D. A. (2003). Swimming Speed, Stroke Rate and Stroke Length During Maximal 100 m Freestyle of Boys 11-16 Years of Age. In J. C. Chatard. (Ed.), *Biomechanics and Medicine in Swimming IX* (pp. 195-201). Saint-Étienne: Publications de l'Université de Saint-Étienne.
- Wakayoshi, K., D'Acquisto, L. J., Cappaert, J. M., & Troup, J. P. (1995). Relationship between oxygen uptake, stroke rate and swimming velocity in competitive swimming. *International Journal of Sports Medicine*, 16(1), 19-23.
- Zamparo, P. (2006). Effects of age and gender on the propelling efficiency of the arm stroke. *European Journal of Applied Physiology*, 97(1), 52-58.
- Zamparo, P., Capelli, C., Cautero, M., & Di Nino, A. (2000). Energy cost of front-crawl swimming at supra-maximal speeds and underwater torque in young swimmers. *European Journal of Applied Physiology*, 83(6), 487-491.
- Zamparo, P., Capelli, C., & Pendergast, D. (2011). Energetics of swimming: A historical perspective. *European Journal of Applied Physiology*, 111(3), 367-378.
- Zamparo, P., Gatta, G., Pendergast, D., & Capelli, C. (2009). Active and passive drag: The role of trunk incline. *European Journal of Applied Physiology*, 106(2), 195-205.
- Zamparo, P., Lazzer, S., Antoniazzi, C., Cedolin, S., Avon, R., & Lesa, C. (2008). The interplay between propelling efficiency, hydrodynamic position and energy cost of front crawl in 8 to 19-year-old swimmers. *European Journal of Applied Physiology*, 104(4), 689-699.
- Zamparo, P., & Swaine, I. L. (2012). Mechanical and propelling efficiency in swimming derived from exercise using a laboratory-based whole-body swimming ergometer. *Journal of Applied Physiology*, 113(4), 584-594.

Chapter 9

- Alberty, M., Potdevin, F., Dekerle, J., Pelayo, P., Gorce, P., & Sidney, M. (2008). Changes in swimming technique during time to exhaustion at freely chosen and controlled stroke rates. *Journal of Sports Sciences*, 26(11), 1191-1200.
- Alberty, M., Sidney, M., Huot-Marchand, F., Hespel, J. M., & Pelayo, P. (2005). Intracyclic velocity variations and arm coordination during exhaustive exercise in front crawl stroke. *International Journal of Sports Medicine*, 26(6), 471-475.
- Anderson, G. S., & Rhodes, E. C. (1991). Relationship between blood lactate and excess CO₂ in elite cyclists. *Journal of Sports Sciences*, 9(2), 173-181.
- Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010a). Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. *Journal of Science and Medicine in Sport*, 13(2), 262-269.
- Barbosa, T. M., Costa, M., Marinho, D. A., Coelho, J., Moreira, M., & Silva, A. J. (2010b). Modeling the links between young swimmers' performance: Energetic and biomechanic profiles. *Pediatric Exercise Science*, 22(3), 379-391.
- Bartlett, R. M. (2007). *Introduction to Sports Biomechanics. Analysing Human Movement Patterns*. New York: Routledge.

- Bentley, D. J., Roels, B., Hellard, P., Fauquet, C., Libicz, S., & Millet, G. P. (2005). Physiological responses during submaximal interval swimming training: Effects of interval duration. *Journal of Science and Medicine in Sport*, 8(4), 392-402.
- Berger, M. A. M., de Groot, G., & Hollander, A. P. (1995). Hydrodynamic drag and lift forces on human hand/arm models. *Journal of Biomechanics*, 28(2), 125-133.
- Berger, M. A. M., Hollander, A. P., & De Groot, G. (1999). Determining propulsive force in front crawl swimming: A comparison of two methods. *Journal of Sports Sciences*, 17(2), 97-105.
- Costill, D. L., Lee, G., & D'Acquisto, L. J. (1987). Video-computer assisted analysis of swimming technique. *Journal of Swimming Research*, 3, 5-9.
- Craig, A., Termin, B., & Pendergast, D. (2006). Simultaneous recordings of velocity and video during swimming. *Portuguese Journal of Sports Science*, 6, 32-35.
- Dal Monte, A., Sardella, F., Alippi, B., Faina, M., & Manetta, A. (1994). A new respiratory valve system for measuring oxygen uptake during swimming. *European Journal of Applied Physiology* 69(2), 159-162.
- Davids, K., Button, C., & Bennett, S. J. (2008). *Dynamics of skill acquisition: a constraints-led approach*. Champaign, IL: Human Kinetics Publishers.
- Deschodt, J., Arsac, L., & Rouard, A. (1999). Relative contribution of arms and legs in humans to propulsion in 25-m sprint front-crawl swimming. *Eur J Appl Physiol*, 3(80), 192-199.
- Espinosa, H. G., Nordsborg, N., & Thiel, D. V. (2015). *Front crawl swimming analysis using accelerometers: A preliminary comparison between pool and flume*. Comunicação apresentada em Procedia Engineering.
- Fernandes, R. J. & Vilas-Boas, J. P. (2012). Time to exhaustion at the VO₂max velocity in swimming: A review. *Journal of Human Kinetics*, 32(1), 121-134.
- Fernandes, R. J., Sousa, M., Pinheiro, A., Vilar, S., Colaço, P., & Vilas-Boas, J. P. (2010). Assessment of individual anaerobic threshold and stroking parameters in swimmers aged 10-11 years. *European Journal of Sport Science*, 10(5), 311-317.
- Figueiredo, P., Pendergast, D. R., Vilas-Boas, J. P., & Fernandes, R. J. (2013a). Interplay of biomechanical, energetic, coordinative, and muscular factors in a 200 m front crawl swim. *BioMed Research International*, 2013.
- Figueiredo, P., Toussaint, H. M., Vilas-Boas, J. P., & Fernandes, R. J. (2013b). Relation between efficiency and energy cost with coordination in aquatic locomotion. *European Journal of Applied Physiology*, 113(3), 651-659.
- Figueiredo, P., Vilas Boas, J. P., Maia, J., Gonçalves, P., & Fernandes, R. J. (2009). Does the hip reflect the centre of mass swimming kinematics? *International Journal of Sports Medicine*, 30(11), 779-781.
- Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J. P., & Fernandes, R. J. (2011). An energy balance of the 200 m front crawl race. *European Journal of Applied Physiology*, 111(5), 767-777.
- Gayda, M., Bosquet, L., Juneau, M., Guiraud, T., Lambert, J., & Nigam, A. (2010). Comparison of gas exchange data using the Aquatrainer® system and the facemask with Cosmed K4b2 during exercise in healthy subjects. *European Journal of Applied Physiology*, 109(2), 191-199.
- Glazier, P. S., Wheat, J. S., Pease, D., & Bartlett, R. M. (2006). Dynamic systems theory and the functional role of movement variability. In K. Davids, S. J. Bennett & K. Newell (Eds.), *Movement system variability*. Champaign, IL: Human Kinetics Publishers.
- Gourgoulis, V., Boli, A., Aggeloussis, N., Toubekis, A., Antoniou, P., Kasimatis, P., Vezos, N., Michalopoulou, M., Kambas, A., & Mavromatis, G. (2014). The effect of leg kick on sprint front crawl swimming. *Journal of Sports Sciences*, 32(3), 278-289.
- Hawley, J. A., Williams, M. M., Vickovic, M. M., & Handcock, P. J. (1992). Muscle power predicts freestyle swimming performance. *British Journal of Sports Medicine*, 26(3), 151-155.
- Keskinen, K., & Komi, P. V. (1993). Stroking characteristics of front crawl swimming during exercise. *Journal of Applied Biomechanics*, 9(3), 219-226.
- Keskinen, K. L., & Keskinen, O. P. (1999). Performance test for swimmers — a new approach utilising pace-maker lights — a pilot study. In K. L. Keskinen, P. V. Komi & A. P. Hollander (Eds.), *Biomechanics and Medicine in Swimming VIII* (pp. 245-248). Jyväskylä: University of Jyväskylä.

- Keskinen, K. L., Rodriguez, F. A., & Keskinen, O. P. (2003). Respiratory snorkel and valve system for breath-by-breath gas analysis in swimming. *Scandinavian Journal of Medicine and Science in Sports*, 13(5), 322-329.
- Kjendlie, P. L., & Olstad, B. H. (2012). Automatic 3D motion capture of swimming: marker resistance. *Medicine and Science in Sports and Exercise*, 44(5), S320.
- Koga, S., Shiojiri, T., Shibasaki, M., Fukuba, Y., Fukuoka, Y., & Kondo, N. (1996). Kinetics of oxygen uptake and cardiac output at onset of arm exercise. *Respiration Physiology*, 103(2), 195-202.
- Komar, J., Leprêtre, P. M., Alberty, M., Vantorre, J., Fernandes, R. J., Hellard, P., Chollet, D., & Seifert, L. (2012). Effect of increasing energy cost on arm coordination in elite sprint swimmers. *Human Movement Science*, 31(3), 620-629.
- Mader, A., Heck, H., & Hollman, W. (1978). Evaluation of lactic acid anaerobic energy contribution by determination of post exercise lactic acid concentration of ear capillary blood in middle-distance runners and swimmers. In F. Landry & W. Orban (Eds.), *Exercise Physiology. Symposia Specialists* (pp. 187-200). Miami.
- Magalhaes, F. A., Sawacha, Z., Di Michele, R., Cortesi, M., Gatta, G., & Fantozzi, S. (2013). Effectiveness of an automatic tracking software in underwater motion analysis. *Journal of Sports Science and Medicine*, 12(4), 660-667.
- Maglischo, E. W. (2003). *Swimming fastest: The essential reference on technique, training, and program design*. Champaign, IL: Human Kinetics Publisher.
- Martin, R. B., Yeater, R. A., & White, M. K. (1981). A simple analytical model for the crawl stroke. *Journal of Biomechanics*, 14(8), 539-548.
- Ogita, F., Onodera, T., Tamaki, H., Toussaint, H., Hollander, P., & Wakayoshi, K. (2003). Metabolic Profile During Exhaustive Arm Stroke, Leg Kick and Whole Body Swimming Lasting 15 s to 10 min. In J. C. Chatard (Ed.), *Biomechanics and Medicine in Swimming IX* (pp. 361-367). Saint-Étienne: Publications de l'Université de Saint-Étienne.
- Olbrecht, J. (2000). *The science of winning. Planning, periodizing and optimizing swim training*. Luton: Swimshop.
- Pendergast, D. R., Capelli, C., Craig, A., Di Prampero, P. E., Minetti, A. E., Mollendorf, J., Termin, A., & Zamparo, P. (2006). Biophysics in swimming. In J. P. Vilas-Boas, F. Alves & A. Marques (Eds.), *Xth International Symposium of Biomechanics and Medicine in Swimming* (pp. 185-189). Porto, Portugal.
- Pessôa Filho, D. M., Greco, C. C., & Denadai, B. S. (2014). Tether-power at maximal lactate steady-state and endurance indexes of swimming performance. *Brazilian Journal of Sports Medicine*, 20(5), 359-365.
- Psycharakis, S. G., Cooke, C. B., Paradisis, G. P., O'Hara, J., & Phillips, G. (2008). Analysis of selected kinematic and physiological performance determinants during incremental testing in elite swimmers. *Journal of Strength and Conditioning Research*, 22(3), 951-957.
- Pyne, D. B., & Sharp, R. L. (2014). Physical and energy requirements of competitive swimming events. *International Journal of Sport Nutrition and Exercise Metabolism*, 24(4), 351-359.
- Reis, J. F., Alves, F. B., Bruno, P. M., Vleck, V., & Millet, G. P. (2012). Effects of aerobic fitness on oxygen uptake kinetics in heavy intensity swimming. *European Journal of Applied Physiology*, 112(5), 1689-1697.
- Rodriguez, F. A., Keskinen, K. L., Keskinen, O. P., & Malvela, M. (2003). Oxygen Uptake Kinetics During Free Swimming: A Pilot Study. In J. C. Chatard (Ed.), *Biomechanics and Medicine in Swimming IX* (pp. 379-385). Saint-Étienne: Publications de l'Université de Saint-Étienne.
- Rodriguez, F. A., Keskinen, K. L., Kusch, M., & Hoffmann, U. (2008). Validity of a swimming snorkel for metabolic testing. *International Journal of Sports Medicine*, 29(2), 120-128.
- Roels, B., Schmitt, L., Libicz, S., Bentley, D., Richalet, J. P., & Millet, G. (2005). Specificity of $\dot{V}O_{2max}$ and the ventilatory threshold in free swimming and cycle ergometry: Comparison between triathletes and swimmers. *British Journal of Sports Medicine*, 39(12), 965-968.
- Schnitzler, C., Seifert, L., Alberty, M., & Chollet, D. (2010). Hip Velocity and Arm Coordination in Front Crawl Swimming. *International Journal of Sports Medicine*, 31, 875-881.
- Seifert, L., Boulesteix, L., Carter, M., & Chollet, D. (2005). The spatial-temporal and coordinative structures in elite male 100-m front crawl swimmers. *International Journal of Sports*

- Medicine*, 26(4), 286-293.
- Seifert, L., & Chollet, D. (2009). Modelling spatial-temporal and coordinative parameters in swimming. *Journal of Science and Medicine in Sport*, 12(4), 495-499.
- Seifert, L., Komar, J., Barbosa, T., Toussaint, H., Millet, G., & Davids, K. (2014). Coordination Pattern Variability Provides Functional Adaptations to Constraints in Swimming Performance. *Sports Medicine*.
- Seifert, L., Komar, J., Lepitre, P. M., Lemaitre, F., Chavallard, F., Alberty, M., Houel, N., Hausswirth, C., Chollet, D., & Hellard, P. (2010a). Swim specialty affects energy cost and motor organization. *International Journal of Sports Medicine*, 31(9), 624-630.
- Seifert, L., Toussaint, H. M., Alberty, M., Schnitzler, C., & Chollet, D. (2010b). Arm coordination, power, and swim efficiency in national and regional front crawl swimmers. *Human Movement Science*, 29(3), 426-439.
- Smith, D. J., Norris, S. R., & Hogg, J. M. (2002). Performance evaluation of swimmers: Scientific tools. *Sports Medicine*, 32(9), 539-554.
- Sousa, A., Figueiredo, P., Pendergast, D., Kjendlie, P., Vilas-Boas, J., & Fernandes, R. (2014). Critical Evaluation of Oxygen Uptake Assessment in Swimming. *International Journal of Sports Physiology and Performance*, 9(2), 190-202.
- Sousa, A., Rodríguez, F. A., Machado, L., Vilas-Boas, J. P., & Fernandes, R. J. (2015). Exercise modality effect on oxygen uptake off-transient kinetics at maximal oxygen uptake intensity. *Experimental Physiology*, 100(6), 719-729.
- Thompson, K. G., Atkinson, G., MacLaren, D. P. M., & Lees, A. (2004). Reliability of metabolic and stroke-cycle responses during sub-maximal breaststroke swimming. *Journal of Human Movement Studies*, 46(1), 35-54.
- Toussaint, H. (2011). Biomechanics of drag and propulsion in front crawl swimming. In L. Seifert, D. Chollet & I. Mujika (Eds.), *World book of swimming: From science to performance* (pp. 3-20). New York: Nova Science Publishers, Inc.
- Toussaint, H. M., Carol, A., Kranenborg, H., & Truijens, M. J. (2006). Effect of fatigue on stroking characteristics in an arms-only 100-m front-crawl race. *Medicine and Science in Sports and Exercise*, 38(9), 1635-1642.
- Toussaint, H. M., de Groot, G., Savelberg, H. H. C. M., Vervoorn, K., Hollander, A. P., & Van Ingen Schenau, G. J. (1988). Active drag related to velocity in male and female swimmers. *Journal of Biomechanics*, 21(5), 435-438.
- Toussaint, H. M., Meulemans, A., de Groot, G., Hollander, A. P., Schreurs, A. W., & Vervoorn, K. (1987). Respiratory valve for oxygen uptake measurements during swimming. *European Journal of Applied Physiology* 56(3), 363-366.
- Vorontsov, A. R. (2011). Strength and power training in swimming. In L. Seifert, D. Chollet & I. Mujika (Eds.), *World book of swimming: from science to performance* (pp. 313-343). New York: Nova Science Publishers, Inc.
- Vorontsov, A. R., & Binevsky, D. A. (2003). Swimming Speed, Stroke Rate and Stroke Length During Maximal 100 m Freestyle of Boys 11-16 Years of Age. In J. C. Chatard. (Ed.), *Biomechanics and Medicine in Swimming IX* (pp. 195-201). Saint-Étienne: Publications de l'Université de Saint-Étienne.
- Wasserman, K., Whipp, B. J., Koyal, S. N., & Beaver, W. L. (1973). Anaerobic threshold and respiratory gas exchange during exercise. *Journal of Applied Physiology*, 35(2), 236-243.
- Wilmore, J. H., & Costill, D. L. (1999). *Physiology of sport and exercise*. Champaign, Illinois: Human Kinetics Publisher.

Appendix I

- Abdel-Aziz, Y. I., & Karara, H. M. (1971). Direct linear transformation from comparator coordinates into object space coordinates in close range photogrammetry. In *Proceedings of the American Society of Photogrammetry Symposium on Close Range Photogrammetry* (pp. 1-18). Church Falls.
- Alberty, M., Sidney, M., Huot-Marchand, F., Hespel, J. M., & Pelayo, P. (2005). Intracyclic velocity variations and arm coordination during exhaustive exercise in front crawl stroke.

- International Journal of Sports Medicine*, 26(6), 471-475.
- Allard, P., Blanchi, J. P., & Aïssaoui, R. (1995). Bases of three-dimensional reconstruction. In P. Allard, I. Stokes & J. P. Blanchi (Eds.), *Three-dimensional analysis of human movement* (pp. 19-40). Champaign: Human kinetics.
- Barbosa, T., Santos Silva, J. V., Sousa, F., & Vilas-Boas, J. P. (2003). *Comparative study of the response of kinematical variables from the hip and the center of mass in butterflyers*. Comunicação apresentada em Biomechanics and Medicine in Swimming IX. University of St Etienne Publications.
- Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010). Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. *Journal of Science and Medicine in Sport*, 13(2), 262-269.
- Barbosa, T. M., Fernandes, R. J., Morouco, P., & Vilas-Boas, J. P. (2008). Predicting the intra-cyclic variation of the velocity of the centre of mass from segmental velocities in butterfly stroke: A pilot study. *Journal of Sports Science and Medicine*, 7(2), 201-209.
- Barbosa, T. M., Lima, F., Portela, A., Novais, D., Machado, L., Colaço, P., Gonçalves, P., Fernandes, R., Keskinen, K. L., & Vilas-Boas, J. P. (2006). *Relationships between energy cost, swimming velocity and speed fluctuation in competitive swimming strokes*. Comunicação apresentada em Biomechanics and Medicine in Swimming X. Portuguese Journal of Sports Science.
- Bartlett, R. M. (2007). *Introduction to Sports Biomechanics. Analysing Human Movement Patterns*. (Second ed.). New York: Routledge.
- Costill, D. L., Lee, G., & D'Acquisto, L. (1987). Video-computer assisted analysis of swimming technique. *Journal of Swimming Research*(3), 5-9.
- Craig, A., Termin, B., & Pendergast, D. (2006). *Simultaneous recordings of velocity and video during swimming*. Comunicação apresentada em Biomechanics and Medicine in Swimming X. Portuguese Journal of Sports Science.
- Craig, A. B., Jr., & Pendergast, D. R. (1979). Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. *Medicine and Science in Sports and Exercise*, 11(3), 278-283.
- De Leva, P. (1996). Adjustments to zatsiorsky-seluyanov's segment inertia parameters. *Journal of Biomechanics*, 29(9), 1223-1230.
- Fernandes, R. J., Keskinen, K. L., Colaço, P., Querido, A. J., Machado, L. J., Morais, P. A., Novais, D. Q., Marinho, D. A., & Vilas Boas, J. P. (2008). Time limit at VO_{2max} velocity in elite crawl swimmers. *International Journal of Sports Medicine*, 29(2), 145-150.
- Fernandes, R. J., Sousa, M., Pinheiro, A., Vilar, S., Colaço, P., & Vilas-Boas, J. P. (2010). Assessment of individual anaerobic threshold and stroking parameters in swimmers aged 10-11 years. *European Journal of Sport Science*, 10(5), 311-317.
- Figueiredo, P., Machado, L., Vilas-Boas, J. P., & Fernandes, R. J. (2011). Reconstruction Error of Calibration Volume's Coordinates for 3D Swimming Kinematics. *J Hum Kinet*, 29, 35-40.
- Figueiredo, P., Vilas Boas, J. P., Maia, J., Goncalves, P., & Fernandes, R. J. (2009). Does the hip reflect the centre of mass swimming kinematics? *Int J Sports Med*, 30(11), 779-781.
- Holmér, I. (1979). Analysis of acceleration as a measure of swimming proficiency. . In J. Terauds & E. W. Bedingfield (Eds.), *Swimming III*. Baltimore: University Park Press.
- Maglischo, C. W., Maglischo, E. W., & Santos, T. R. (1987). The relationship between the forward velocity of the center of gravity and the forward velocity of the hip in the four competitive strokes. *Journal of Swimming Research*(3), 11-17.
- Olbrecht, J. (2000). *The science of winning. Planning, periodizing and optimizing swim training*. Luton: Swimshop.
- Plagenhoef, S. C. (1976). Methods for obtaining kinetic data to analyze human motions. In T. P. Martin (Ed.), *Biomechanics of Sport - Selected Readings* (pp. 124-133). New York: State University of New York.
- Psycharakis, S. G., Naemi, R., Connaboy, C., McCabe, C., & Sanders, R. H. (2010). Three-dimensional analysis of intracycle velocity fluctuations in frontcrawl swimming. *Scand J Med Sci Sports*, 20(1), 128-135.
- Psycharakis, S. G., & Sanders, R. H. (2009). Validity of the use of a fixed point for intracycle velocity calculations in swimming. *J Sci Med Sport*, 12(2), 262-265.
- Schnitzler, C., Seifert, L., Alberty, M., & Chollet, D. (2010). Hip velocity and arm coordination in

- front crawl swimming. *Int J Sports Med*, 31(12), 875-881.
- Schnitzler, C., Seifert, L., & Chollet, D. (2009). Variability of coordination parameters at 400-m front crawl swimming pace. *J Sports Sci Med*, 8(2), 203-210.
- Seifert, L., & Chollet, D. (2009). Modelling spatial-temporal and coordinative parameters in swimming. *J Sci Med Sport*, 12(4), 495-499.
- Seifert, L., Leblanc, H., Chollet, D., & Delignieres, D. (2010). Inter-limb coordination in swimming: effect of speed and skill level. *Hum Mov Sci*, 29(1), 103-113.
- Smith, D. J., Norris, S. R., & Hogg, J. M. (2002). Performance evaluation of swimmers: scientific tools. *Sports Med*, 32(9), 539-554.
- Tella, V., Toca-Herrera, J. L., Gallach, J. E., Benavent, J., Gonzalez, L. M., & Arellano, R. (2008). Effect of fatigue on the intra-cycle acceleration in front crawl swimming: a time-frequency analysis. *J Biomech*, 41(1), 86-92.
- Vilas-Boas, J. P., Fernandes, R. J., Barbosa, T. M., & performance, I. W. b. o. s. f. s. t. (2010). Intra-cycle velocity variations, swimming economy, performance and training in swimming. In L. Seifert, D. Chollet & I. Mujika (Eds.), *Nova Science Publishers Inc.* (pp. 120-140).

Appendix II

- Armstrong L, Balady GJ, & MJ, B. (2006). *ACSM's Guidelines for Exercise Testing and Prescription* (7th ed.). Baltimore, USA: Williams and Wilkins.
- Bland, J. M., & D.G., A. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*, 1, 307-310.
- Brugnoli, P. (2010). Letter to the editor of EJAP. 4(110), 875-876.
- Crandall, C., Taylor, S., & Raven, P. (1994). Evaluation of the Cosmed K2 portable telemetric oxygen uptake analyzer. *Med Sci Sports Exerc* 1(26), 108-111.
- Dal Monte, A., Sardella, F., Alippi, B., Faina, M., & Manetta, A. (1994). A new respiratory valve system for measuring oxygen uptake during swimming. *European Journal of Applied Physiology* 69(2), 159-162.
- Di Prampero, P. E., Pendergast, D. R., Wilson, D. W., & Rennie, D. W. (1974). Energetics of swimming in man. *Journal of Applied Physiology*, 37(1), 1-5.
- Douglas, C. (1911). A method for determining the total respiratory exchange in man. *J Physiol*(42), 17-18.
- Doyon, K., Perrey, S., Abe, D., & Hughson, R. (2001). Field testing of $\dot{V}O_{2peak}$ in cross-country skiers with portable breath-by-breath system. *Can J Appl Phys*, 1(26), 1-11.
- Duffield, R., Dawson, B., Pinnington, H., & Wong, P. (2004). Accuracy and reliability of a Cosmed K4b2 portable gas analysis system. *J Sci and Med in Sport*, 1(7), 11-22.
- Fernandes, R. J., Sousa, M., MacHado, L., & Vilas-Boas, J. P. (2011). Step length and individual anaerobic threshold assessment in swimming. *International Journal of Sports Medicine*, 32(12), 940-946.
- Gayda, M. (2011). Response to the letter of M. Brugnoli. *Eur J Appl Physiol Occup Physiol*, 5(111), 895-896.
- Gayda, M., Bosquet, L., Juneau, M., Guiraud, T., Lambert, J., & Nigam, A. (2010). Comparison of gas exchange data using the Aquatrainer® system and the facemask with Cosmed K4b2 during exercise in healthy subjects. *European Journal of Applied Physiology*, 109(2), 191-199.
- Harriss, D. J., & Atkinson, G. (2011). Update – Ethical Standards in Sport and Exercise Science Research. *Int J Sports Med.*, 32(11), 819-821.
- Hauswirth, C., Bigard, A. X., & Le Chevalier, J. M. (1997). The Cosmed K4 Telemetry System as an Accurate Device for Oxygen Uptake Measurements during Exercise. *Int J Sports Med.*, 28(06), 449-453.
- Holmér, I. (1972). Oxygen uptake during swimming in man. *Journal of Applied Physiology*, 33(4), 502-509.
- Holmer, I., & Astrand, P. (1972). Swimming training and maximal oxygen uptake. *Journal of Applied Physiology*, 33(4), 510-513.
- Kawakami, Y., Nozaki, D., Matsuo, A., & Fukunaga, T. (1992). Reliability of measurement of

- oxygen uptake by a portable telemetric system. *European Journal of Applied Physiology and Occupational Physiology*, 65(5), 409-414.
- Keskinen, K. L., Rodriguez, F. A., & Keskinen, O. P. (2003). Respiratory snorkel and valve system for breath-by-breath gas analysis in swimming. *Scandinavian Journal of Medicine and Science in Sports*, 13(5), 322-329.
- Lavoie, J. M., & Montpetit, R. R. (1986). Applied physiology of swimming. *Sports Medicine*, 3, 165-189.
- Lucia, A., Fleck, S., Gotshall, R., & Kearney, J. (1993). Validity and reliability of the Cosmed K2 instrument. *International Journal of Sports Medicine*, 14(7), 380-386.
- McLaughlin, J. E., King, G. A., Howley, E. T., Bassett Jr, D. R., & Ainsworth, B. E. (2001). Validation of the COSMED K4 b2 Portable Metabolic System. *Int J Sports Med.*, 22(04), 280-284.
- Özyener, F., Rossiter, H., Ward, S., & Whipp, B. (2001). Influence of exercise intensity on the on- and off-transient kinetics of pulmonary oxygen uptake in humans. *The Journal of Physiology*, 533(3), 891-902.
- Passing, H., & Bablok, W. (1983). A new biometrical procedure for testing the equality of measurements from two different analytical methods. Application of linear regression procedures for method comparison studies in clinical chemistry. Part I. *Journal of Clinical Chemistry and Clinical Biochemistry*, 21(11), 709-720.
- Peel, C., & Utsey, C. (1993). Oxygen consumption using the K2 telemetry system and a metabolic cart. *Medicine & Science in Sports & Exercise*, 25(3), 396-400.
- Pendergast, D. R., Di Prampero, P. E., Craig, A. B., Jr., Wilson, D. R., & Rennie, D. W. (1977). Quantitative analysis of the front crawl in men and women. *Journal of Applied Physiology*, 43(3), 475-479.
- Reis, V. M., Marinho, D. A., Polcarpo, F. B., Carneiro, A. L., Baldari, C., & Silva, A. J. (2010). Examining the accumulated oxygen deficit method in front crawl swimming. *International Journal of Sports Medicine*, 31(6), 421-427.
- Rodriguez, F. A., Keskinen, K. L., Kusch, M., & Hoffmann, U. (2008). Validity of a swimming snorkel for metabolic testing. *International Journal of Sports Medicine*, 29(2), 120-128.
- Sousa, A., Figueiredo, P., Oliveira, N., Oliveira, J., Silva, A., Keskinen, K., Rodriguez, F., Machado, L., Vilas-Boas, J., & Fernandes, R. (2011). VO₂ kinetics in 200-m race-pace front crawl swimming. *International Journal of Sports Medicine*, 32(10), 765-770.
- Toussaint, H. M., Knops, W., De Groot, G., & Hollander, A. P. (1990). The mechanical efficiency of front crawl swimming. *Medicine and Science in Sports and Exercise*, 22(3), 402-408.
- Toussaint, H. M., Meulemans, A., de Groot, G., Hollander, A. P., Schreurs, A. W., & Vervoorn, K. (1987). Respiratory valve for oxygen uptake measurements during swimming. *European Journal of Applied Physiology* 56(3), 363-366.
- Vilas-Boas, J. P., & Santos, P. (1994). Comparison of swimming economy in three breaststroke techniques. In M. Miyashita, Y. Mutoh & A. Richardson (Eds.), *Medicine and Science in Aquatic Sports—10th FINA World Sport Medicine Congress* (pp. 104-109). Honolulu: HI: Karger.